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NAVARES: A PROTOTYPE EXPERT SYSTEM

FOR NAVSTAR ANOMALY RESOLUTION

THESIS

Michael A. Rampino
Captain, USAF

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The operational NAVSTAR Global Positioning System (GPS) satellite constellation is operated by entirely U.S. Air Force military personnel. The "Blue Suit" satellite engineers must meet the challenge posed by on-orbit anomalies wihtout the extensive contractor ~~technical~~ support available to most satellite systems in the past. These engineers are generally less experienced than their contemporaries in other systems, but most importantly, tthey will take their expertise with them when they leave for a new assignment.

The objective of this research was to demonstrate the ability of expert systems to maintain corporate knowledge, aid inexperienced satellite engineers, and take advantage of the "economies of scale" possible by developing the system for a many satellite constellation.

NAVARES, the NAVSTAR Anomaly Resolution Expert System, is a rule-based expert system prototype that successfully diagnoses many anomalies in the Attitude, Velocity and Control Subsystem, and the Electrical Power Subsystem of the NAVSTAR satellites. Anomaly Resolution heuristics and procedures are represented in the knowledge base with rules and procedural code. The user interacts with NAVARES by answering system queries about the status of subsystem components. NAVARES uses its expert knowledge to diagnose the satellite anomaly and recommend a remedy. The output consists of the diagnosis, remedy, and titles of relevant past anomaly reports. (Theses)

AFIT/GSO/ENS/87D-10

NAVARES: A PROTOTYPE EXPERT SYSTEM FOR NAVSTAR ANOMALY RESOLUTION

THESIS

Presented to the Faculty of the School of Engineering

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the

Requirements for the Degree of

Master of Science in Space Operations

Michael A. Rampino, B.S.

Captain, USAF

December 1987

Preface

The purpose of this thesis was to demonstrate the applicability of expert systems to the domain of satellite command and control, specifically, NAVSTAR anomaly resolution. A prototype expert system was constructed which successfully handles many Attitude, Velocity and Control Subsystem and Electrical Power Subsystem anomalies. The project was sponsored by the USAF Space Command's Second Space Wing (2 SW) with extensive support by the Second Satellite Control Squadron (2 SCS).

The topic was suggested by Capt Cecil Longino of the 2 SW who also helped make TDY funds available. Others instrumental in the project's success were Maj Mike Shaw, Capt Dale Wilson, and, especially, Lt Gil Villanueva, all of the 2 SCS. Closer to home, my classmate, Capt Ed Crawford, was a constant source of encouragement and friendship. Capt Bob Hammell and Lt Steve Wagner helped by sharing the "secrets" of Guru. Of course, my advisor Lt Col Greg Parnell must receive credit and thanks for his professional guidance and many insights. If I learned from this research effort, it was because he let me make the tough decisions.

I also wish to thank my beautiful wife, Capt Lisa Rampino, for enduring our physical separation during our first 15 months of marriage and for the many long distance counseling sessions.

Finally, this thesis is dedicated to the men and women of the Service Cryptologic Elements who perform their duty around the clock in defense of their nation without the hope of recognition from their countrymen.

Michael A. Rampino

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Abstract

The Operational NAVSTAR Global Positioning System (GPS) satellite constellation is operated entirely by U.S. Air Force military personnel. The "Blue Suit" satellite engineers must meet the challenge posed by on-orbit anomalies without the extensive contractor technical support available to most satellite systems in the past. These engineers are generally less experienced than their contemporaries in other systems, but, most importantly, they will take their expertise with them when they leave for a new assignment.

The objective of this research was to demonstrate the ability of expert systems to maintain corporate knowledge, aid inexperienced satellite engineers, and take advantage of the "economies of scale" possible by developing the system for a many satellite constellation.

The NAVSTAR Anomaly Resolution Expert System (NAVARES) is a rule-based expert system prototype that successfully handles many anomalies in the Attitude, Velocity and Control Subsystem (AVCS) and the Electrical Power Subsystem (EPS). Anomaly resolution procedures and heuristics are represented in the knowledge base with rules and procedural code. The user interacts with NAVARES by answering system queries about the status of the satellite. NAVARES uses its expert knowledge to diagnose the satellite anomaly and recommend a remedy. The output consists of the diagnosis, remedy, and titles of relevant past anomaly reports.

NAVARES: A PROTOTYPE EXPERT SYSTEM FOR NAVSTAR ANOMALY RESOLUTION

I. Introduction

Background

Artificial Intelligence (AI) means different things to different people. In general, AI can be defined as "the study of how to r computers do things, at which, at the moment, people are better" (24:1). This definition encompasses many active and potentially fruitful research areas such as machine vision, robotics, natural language understanding, and knowledge based or expert systems. The area which appears to have the greatest potential for bearing fruit in the near term, particularly for satellite command and control applications, is expert systems (26:29).

Expert systems emerged within the last decade. In the early days of AI research, scientists concentrated on trying to simulate the human thought process by finding general methods for solving broad classes of problems (24:2) The results were less than satisfying for "real world" applications. But, in the early seventies, researchers began concentrating on other ways to make computers "intelligent" (28:4). They tried to find ways to represent problems that would make them easier to solve, and to find clever ways to search for a solution so that computation time and the necessary memory capacity could be minimized. In the late seventies came the realization that the power of a program comes will not be completely reacted. As the rate of reaction is slowed the maximum thickness of carbon must also be reduced since there is a much smaller temperature excursion to aid reaction. While relatively large carbon particles (>100 μm) can be fully reacted with large exotherms this is to be avoided since it generally coarsens both the resulting silicon carbide and causes silicon lakes due to solution and reprecipitation or may cause cracking.

It is also necessary to decrease the maximum particle size as the skeleton density is raised particularly in the range where the residual silicon is below 10 Vol%. In this case the flow is slower due to the lower volume of delivery channels and each particle is further from its reactant supply. Previous efforts[2] showed that the maximum size should be below 10 μm for complete reaction with a skeleton density in the range of .8 to .85 gm/cm^3. It has been found that at higher densities that the maximum size needs to be further reduced, probably to less than 2 μm.

In the current period several dozen different batches have been produced aiming at a pore/particle size less than 1 μm and the range ~1-3 μm. Several of these have been made in two density levels so that processing and properties can be evaluated as a function of residual silicon content.

The carbon skeleton can be shaped in several ways. It may be cast or machined in the polymerized state or machined after carbonization. Each has advantages in certain cases.

from the knowledge it possesses, not just the formalisms and inference schemes it uses. Thus the term "expert system" has come to describe a computer program that has a great deal of specific knowledge about a problem area that is generally very narrow and well bounded.

Expert systems may have applications in the area of satellite command and control. Maj. Robert J. Kruchten, program manager of the U.S. Air Force's Satellite Autonomy Program, has outlined some problems in satellite command and control that expert systems may be able to solve. (14:1) The problem areas can be categorized as dealing with people or time.

The people problems stem from several sources. It takes years to train an individual who is expert in resolving anomalies aboard a given satellite. As satellites become longer and longer lived, it becomes more difficult to retain these experts over the lifetime of the satellite. The increasing number of satellites on orbit today and predicted to be on orbit in the future compounds this dilemma. If the plans for the Strategic Defense Initiative are implemented, there could easily be 100 satellites added to those already on orbit (6:38). And 100 satellites is a conservative estimate. Lastly, the USAF is transferring command and control of many satellite systems to the Air Force Space Command. The Air Force Space Command operators are military members who will rotate positions frequently, taking their expertise with them when they leave for new assignments.

The time problem stems from the fact that some satellite failures may take weeks to resolve. A two-week wait might be acceptable for resolving an anomaly aboard a scientific research satellite, but systems that play a vital role in our nation's security must be returned to normal operations immediately. As space systems play a larger role in defense, as with SDI, response times must be shortened.

This research topic was suggested by Capt Cecil Longino of the Air Force Space Command's Second Space Wing (17). Specifically, he requested that research be conducted to determine the possible applications of AI to two areas: real-time anomaly resolution and automated commanding for a multiple satellite constellation.

Statement of the Problem

The goal of this thesis is to demonstrate the applicability of AI to satellite command and control by developing a prototype expert system. The domain for the prototype is restricted to anomaly resolution for a subset of the possible anomalous conditions aboard the NAVSTAR Global Positioning System (GPS) satellites.

The GPS constellation is a very good target for this research since there are many nearly identical satellites on orbit. Also, command and control of GPS, including anomaly resolution is performed exclusively by Air Force personnel of the Second Satellite Control Squadron (2 SCS). Frequent assignment changes for military personnel mean a constant loss of expertise and an expert system can contribute to maintaining corporate knowledge. However, the NAVSTAR Anomaly Resolution Expert System (NAVARES) is not meant to replace satellite engineers, but to augment their knowledge and expertise.

Scope

A GPS satellite consists of nine subsystems. Due to the time constraint imposed on this research effort only two of these subsystems are diagnosed by the thesis prototype. The Attitude, Velocity and Control Subsystem and the Electrical Power Subsystem were chosen at the suggestion of the 2 SCS Satellite Engineering Branch. In addition, NAVARES does not interface with other equipment or software available at the 2 SCS.

Assumptions

This research effort was conducted with three assumptions in mind. First, the users of the system will be GPS satellite engineers who have at least a basic understanding of the satellites' design and functions. Second, the expert system will not replace human judgement. There will always be a "man in the loop." Third, the prototype will prove useful to the 2 SCS satellite engineers if it is expanded to include the remaining subsystems and maintained to include the latest knowledge of satellite anomalies.

Support Requirements

Access to the experts at the 2 SCS was essential. A two-week visit was made to Falcon AFS, CO to study the problem domain and gather pertinent information. Time was spent in classroom sessions, the Master Control Station (MCS) which is the operational center of the GPS system, and interviewing satellite engineers who perform anomaly resolution. In addition, many telephone interviews and correspondence with the satellite engineers was necessary.

The equipment used to construct the prototype consisted of an IBM Personal Computer (PC) compatible machine, the Zenith 248 with a 20M byte hard disk, and a PC based expert system building tool, Guru (20).

Overview

This chapter has provided a brief introduction and background. Chapter II describes the methodology used to guide this research effort. Chapter III is a survey of the current literature relevant to this work. Chapter IV describes the knowledge engineering phase, and presents background information on GPS operations and an explanation of the GPS anomaly resolution process. Chapter V outlines the system requirements. Chapter VI reviews the system design and implementation process, including tool selection. Chapter VII presents an evaluation of the implemented system. Finally, Chapter VIII outlines research conclusions and recommendations for future efforts.

II. Methodology

Introduction

This thesis research was conducted using the systems approach to problem solving. The project was divided into subtasks to be accomplished in a step-by-step fashion. This chapter presents each step of the process in detail.

Understanding the Problem

A literature review was conducted to determine the progress made in the area of expert systems for satellite anomaly resolution. Chapter III presents the results of this review. A number of prototype systems have been developed and are discussed, but no operational systems were found. The review also addressed the current theoretical approaches to the problem domain.

Satellite Program Selection

The NAVSTAR GPS satellite constellation was selected as the appropriate satellite program to study for three reasons. First, because the GPS constellation consists of many nearly identical satellites on orbit it would be possible to diagnose problems on all the satellites in the constellation with the same system, thus achieving "economies of scale." Also, the satellite engineers who must trouble-shoot problems will face a great work load when the final constellation of 21 satellites is deployed. An expert system has the potential to lighten the load by augmenting the satellite engineers' expertise. Second, and perhaps most important, the GPS system is run exclusively by U.S. Air Force personnel. Frequent assignment changes for military personnel mean a loss of expertise which may be offset by the permanence of an expert system. Third, the fact that the GPS system is largely unclassified meant easy access for the knowledge engineer.

Knowledge Engineering

The knowledge engineering phase is critical to the development of any expert system. It is during this phase that the knowledge of the human expert is captured for inclusion in the knowledge base of the expert system. This task was initiated during a two week visit to the GPS operations center at Falcon AFS, Colorado, but was not completed. It was a continuing effort throughout the development period. Chapter IV addresses the knowledge engineering effort in greater detail.

Identify System Requirements

Before proceeding to select an expert system building tool or knowledge representation language for system implementation, the important step of identifying the system requirements must be accomplished. As a result of the knowledge engineering phase, the necessary input, knowledge base, processing, and output requirements can and must be stated at this point so that the best tool or language may be selected and the proper system design developed. Requirements definition is actually an iterative process requiring the developer to seek feedback from the users at each step in the development phase. The system requirements are identified in chapter V.

System Design

The first step toward system design is selection of an expert system building tool or knowledge representation language (KRL). A KRL can provide more flexibility to a knowledge engineer, but also requires much more programming skill and effort. An expert system building tool provides a structured environment to work with, requiring less programming skill and effort, but it may be less flexible. Of course, there are also cost, hardware and availability constraints which must be taken into account. For this thesis, only tools and languages available at AFIT are considered in the trade-off analysis outlined in Chapter VI.

Once the tool or language is selected, the real work of system design can begin. If a tool rather than a KRL has been selected, then the design process is scoped since the knowledge representation and inferencing scheme may be dictated by the chosen software. However, the manner in which the system requirements will be satisfied should be determined prior to the implementation phase. The knowledge engineer should become intimately familiar with his software during this phase.

Implementation and Evaluation

This last phase is an iterative one. It is now that the prototype is actually implemented based on the knowledge engineer's design. After an initial system is developed it must be evaluated to determine if it is operating as the designer intended (verification) and if its conclusions and recommendations are valid. The latter step, validation, was accomplished by presenting NAVARES with three anomaly scenarios used to evaluate satellite engineers, and having a satellite engineer review the system. Chapter VII presents the results of the evaluation phase.

Summary

The methodology used in this thesis research effort is based on the systems approach to problem solving. The overall task is broken into subtasks which are accomplished sequentially. First, the problem had to understood. Second, a satellite program was chosen. Third, an in-depth understanding of the problem and knowledge used by the expert had to be acquired. Then, the system requirements could be defined, software selected, and a design developed. Finally, the system is implemented and evaluated in an iterative fashion.

III. Literature Review

Topic Statement

The first goal of this review is to present three representative expert systems that deal with the domain of satellite anomaly resolution (see Table I), and also to present the current plans for developing expert systems to support military satellite command and control, specifically anomaly resolution. This discussion provides insight into the problem domain. The second goal is to present a summary of one promising theoretical approach to the general problem of fault diagnosis, i.e., the model-based approach. (References 12, 24, and 28 provide a good introduction to the AI field for those without a strong background in this area. References 18 and 23 provide an overview of expert system applications to Space Operations).

Applications

SCARES. The Satellite Control Anomaly Resolution Expert System (SCARES) is a prototype developed by TRW. Work on the prototype began in late 1985 as a result of funding from the Air Force Satellite Autonomy Program (SAP) (13). The SAP program manager gave the Defense Support Program (DSP) System Program Office (SPO) 400K to develop an expert system prototype to perform anomaly resolution. The SPO chose the attitude control system (ACS) on the DSP satellites as the problem domain.

The motivation for the project came from the desire to develop a mobile control center for DSP that might increase the wartime system survivability. A system like SCARES might replace

Table I. Representative Satellite Diagnostic Systems

SYSTEM NAME	STAGE OF DEVELOPMENT/ RESPONSIBLE AGENCY	SOFTWARE/ HARDWARE ENVIRONMENT	KNOWLEDGE REPRESENTATION	SYSTEM DESCRIPTION
SCARES (SATELLITE CONTROL ANOMALY RESOLUTION EXPERT SYSTEM)	INITIAL PROTOTYPE TRW/SAP FUNDED	ZETALISP/FLAVORS SYMBOLICS 3670	FRAMES/RULES AND OBJECTS	- ANOMALY REOLUTION FOR DSP ATTITUDE CONTROL SUBSYSTEM - FOR MOBILE COMMAND CENTERS - CROSSCHECK TECHNICAL ADVISORS
ADRS (ANOMALY DETECTION AND RESOLUTION SYSTEM)	INITIAL PROTOTYPE IBM/IRAD EFFORT	OPS5 IBM MAINFRAME	RULES AND ATTRIBUTE/VALUE PAIRS QUALITATIVE MODEL OF SYSTEM ELEMENTS	- GENERIC APPROACH TO COMPLEX MILITARY SYSTEM CONTROL - APPLIED TO NAVSTAR L-BAND SUBSYSTEM
STAR-PLAN (SATELLITE ANOMALY RESOLUTION AND PLANNING SYSTEM)	THIRD PROTOTYPE ITERATION FORD/SAP FUNDED	PARAGON XEROX 1108	HYBRID MODELS OF SYSTEM ELEMENTS	- HANDLE MANY ASPECTS OF SATELLITE C2 - FOR MOBILE COMMAND CENTERS AND ON-BOARD DIAGNOSTICS - LATEST PROTOTYPE APPLIED TO NAVSTAR ELECTRICAL SUBSYSTEM

the expert technical advisors who would not accompany a mobile control center. Another motive for developing SCARES was to create a tool that the technical advisors might use to check their own work.

TRW's engineers limited themselves to dealing with a subset of all the possible ACS anomalies and only relatively simple cases (7). A demonstration of SCARES was conducted in late 1986. TRW used a simulator to generate 30 to 40 anomaly cases for SCARES (7). SCARES performed as well or better than human experts given the same anomaly cases (13).

SCARES is no longer funded by the Air Force. The original contract only required the completion of the initial prototype. However, TRW has used their own internal research and development money to continue research into constructing causal models and merging the rule-based and model-based approaches in one system (7).

ADRS. The Anomaly Detection and Resolution System (ADRS) is an internal research and development effort underway at IBM Federal Systems Division (FSD) to develop a generic approach to complex military system control (10:106-110).

Ferneyhough suggests three main incentives for developing ADRS (10). He believes that ADRS can improve the reliability and survivability of complex military systems and reduce their life cycle costs (LCC). Reliability can be improved because the ADRS can check the decisions of novices and experts. Survivability can be improved if the ADRS allows personnel strength at control centers to be cut to the point that it becomes feasible to have mobile facilities for command and control. Finally, if personnel strength is cut there will be corresponding reductions in LCC.

Ferneyhough also lists some requirements for ADRS. Among these requirements are the need for the system to be embeddable into the existing control structure, adaptable, fast, dynamic, and economically feasible (10).

The general ADRS model includes six components: telemetry processing, reference model, anomaly diagnostician, operator interface, recovery planner, and command processing. The telemetry monitor and command processor handle functions that already exist in today's control centers and need not be discussed further. The reference model maintains a model of the expected state of the target system for comparison with actual telemetry data. This approach allows for a richer representation of the knowledge about the system than heuristic rules can provide. Interactions between the system components that might be overlooked when designing a rule-base are inherent in the model. The models of each of the individual components are based on rules and variable attributes. The variable attributes in the component models allow for a reduction in the number of rules required in the system (10).

The anomaly diagnostician uses heuristic knowledge to narrow the source of the fault to one element of the system and flags this information to be presented to the operator. After the human operator examines the system's conclusions and recommendations the recovery planner generates command sequences to resolve the anomaly in accordance with the anomaly diagnostician's and/or human operator's recommendations.

IBM has developed a prototype using the ADRS concepts. The target system was the Global Positioning System Block II spacecraft. No further work has been accomplished on ADRS since the prototype was demonstrated as sought after government funding was not obtained (22).

STAR-PLAN. Ford Aerospace began development of the Satellite Anomaly Resolution and Planning System (STAR-PLAN) in 1983 (11:1-3). The fact that STAR-PLAN is still being worked on today makes it one of the oldest satellite command and control projects in existence. The system is now in its third phase of development.

The first phase of Ford's work (STAR-PLAN I) was targeted at two satellite subsystems, the electric power and distribution system (EPDS) and the tracking, telemetry, and command (TT & C) system. STAR-PLAN I monitors telemetry data, alerts humans to possible problems, isolates faults, and suggests corrections.

STAR-PLAN I was first built in OPS5 on a VAX 11/780 then transferred to a Xerox 1108 and implemented in the Knowledge Engineering Environment (KEE) in July, 1984 (11:3). This initial system included a telemetry simulator for closed loop testing.

The designers at Ford realized that there were limitations with STAR-PLAN I. They needed a wider variety of knowledge representation techniques, and they wanted to avoid the limitations imposed on the system by having to define all resolution procedures and store them as rules (27). The latter limitation meant the system could never handle an unanticipated anomaly.

STAR-PLAN II separates the monitoring, situation assessment, diagnostic, goal determination and planning functions into modules. The monitoring function is performed by the Active Data Base which sends a message to the Situation Assessment module if an event of interest has occurred. The Situation Assessment Module picks the objects (satellite components) involved and sends this information on to the Causal Diagnosis module. The latter module performs causal analysis to determine the root of the problem and generates a list of which objects are malfunctioning. When this list of malfunctioning objects is received by the Goal Determination Module it identifies the goals needed to resolve the anomaly. The last module, Planning and Command, creates a plan for moving from the current state to the goal state and determines the sequence of commands that must be sent to the satellite to accomplish resolution of the anomaly.

The data indicate a standard error for the slope of about 2.7% which would still not reduce the value of $\S_V^R$ enough to fall within the range stated in Ref. 8,

$$.012 < \S_V^R < .020 \tag{5}$$

It should be noted that there is a good deal of uncertainty in the values to assume for K_{IC}, E and even H. For NC203 the values used by reputable authors vary considerably, i.e., H = 19.3 to 24.0 GPa; E = 420 to 448 GPa; K_{IC} = 3 to 5.1 $MPa \cdot M^{1/2}$. While the absolute value for $\S_V^R$ would be affected by the choice of constants this would not account for the disagreement since the same values have been used for each calculation.

The standard error estimate for the experimental slope is less than 3% and was typical of the error found in this study for other silicon carbide based materials. While NC203 was one of the materials studied in Ref. 8, the logrithmatically plotted data given in the publication can not be read accurately enough for a direct comparison. This material was not one chosen as one of the calibration materials for calculating $\S_V^R$.

It is obvious then that quite small changes in the crack propagation behavior as measured by the slope of $c^{3/2}$ vs P can be significantly differentiated but that reflecting these changes into K_{IC} values is much less certain due to uncertainties in the other constants.

By least square fitting of the square of the impression diagonals, a^2, versus load, P, as the independent variable the

This second version of STAR-PLAN is implemented in a Ford developed extension of KEE called "PARAGON" (19:89). PARAGON is a hybrid knowledge representation scheme that incorporates features of several knowledge representation paradigms (8:1-2). The designers attempted to capture the best qualities of rules, objects, classification systems, semantic networks, and blackboards.

The version of STAR-PLAN currently under development, STAR-PLAN III, is also implemented in PARAGON (18:35-36). However, the emphasis in this phase of development is to move further toward the model-based approach, to reason over the differences between the actual telemetry data and the simulation of the expected state of the satellite. "Differential analysis between the simulator and the actual telemetry data will be the primary mechanism for diagnosis and planning" (9:1).

Planned Systems. The Air Force Satellite Control Facility (AFSCF) with the help of the Aerospace Corporation and the NASA Ames Research Center is preparing to contract for four expert system research efforts to support their operations (1;4). Two of these research efforts fall within the satellite anomaly resolution domain. One is the funding of continued research with STAR-PLAN. The other is development of an Intelligent Satellite Monitor (ISM) for DSP.

These two efforts use two different approaches to satellite anomaly resolution. The first effort, STAR-PLAN, will continue progress toward developing an expert system using the model-based approach that may be able to handle unanticipated anomalies. This effort will not produce an operational system in the near term since model-based systems are relatively new and complex when compared to the more familiar rule-based systems. Kruchten suggests that the inability of today's expert systems (rule-based) to handle unanticipated anomalies makes them virtually useless (15). Success with STAR-PLAN could quiet such complaints.

The second effort, ISM, is a response to the need for monitoring the on-orbit spares in the DSP constellation (2;4). The goal for ISM is not to accomplish in-depth anomaly resolution for the satellite, but simply to alert the human operators if a problem develops aboard one of the spares. ISM will continuously monitor the satellites' telemetry data, freeing humans from this task. Since ISM will not be required to perform in-depth diagnosis and remedy tasks the rule-based approach could be used.

The Rome Air Development Center, managing the USAF Satellite Autonomy Program, is also funding research in satellite anomaly resolution (16). Contracts were recently awarded to Ford Aerospace, TRW, and Boeing for research into on-board satellite diagnostic systems.

Model-based Approach

The term "model-based" refers to a general approach to diagnostic systems. These systems "detect failures by identifying discrepancies between observed and expected system behavior" (3:9). The "model" in "model-based" refers to the description of the normal system that is used as a reference for comparison. This model may be qualitative, quantitative, or hybrid (mix of quantitative and qualitative modelling) (3:9-10). In hybrid systems the qualitative code usually acts as the high level control, calling lower level, quantitative portions of the model as "subroutines" (3:10).

One of the seminal works in this field was an attempt to conduct diagnostic reasoning based on structure and behavior. This approach modelled the target system as a network of subsystems with the "lowest level components treated as 'black boxes' which are governed by one or more constraint relations. Faults are declared whenever the observed behavior differs significantly from the expected constrained behavior" (3:9). This work also introduced the concept of "adjacency." "Devices interact because they are in some sense adjacent - electrically adjacent (wired together), physically adjacent (hence thermally connected), electromagnetically adjacent (not shielded) etc" (3:9).

Many proponents of this approach, and of the model-based approach in general, suggest that such a system can handle unexpected or unanticipated anomalies, but given the the description of "adjacency," one can see that modelling any complex physical system is extremely challenging (15;3:12). Some faults will be extremely difficult to diagnose since they result from an unanticipated interaction between "adjacent" components.

Conclusion

The applicability of expert systems technology to the problems of military satellite command and control, specifically anomaly resolution, is recognized in the U.S. Air Force and the defense industry. Several research efforts demonstrate that an expert system based on rules alone is seriously limited in that it cannot deal with unanticipated anomalies. However, the model-based approach to expert system design may avoid this limitation. ADRS and STAR-PLAN demonstrate potentially successful designs.

Since model-based expert systems also entail much greater complexity, cost, and technology levels, along with their better performance, they may not be successfully developed for several years. In this event the simpler and cheaper rule-based approach can be used to solve less demanding problems.

IV. Knowledge Engineering

Introduction

During the two week visit to Falcon AFS, a great deal of effort was spent in simply understanding the problem. Regardless of the fact that a literature review and telephone interviews had been conducted to gain an understanding of the anomaly resolution process, there remained the possibility that close examination of the GPS command and control process would yield a better application or prove GPS satellite anomaly resolution an unsuitable domain for expert system applications.

The 2 SCS introductory course provided some necessary background and understanding of GPS operations before spending two days in the MCS with the Satellite Engineering Officers (SEOs). The SEOs provide the first level of anomaly resolution for the satellites. It is their responsibility to identify Satellite Vehicle (SV) anomalies and resolve them if possible. If the anomaly is serious enough to threaten the health of the SV and cannot be corrected immediately, it is the SEO's responsibility to reconfigure the SV so that it is safe from further degradation.

The remainder of the visit was spent gathering data, attending classroom sessions covering the SV subsystems and requirements, and interviewing Satellite Engineers (SEs) who perform the second level of anomaly resolution, those not on the operational crews. It is the latter group of SEs who perform in-depth anomaly resolution. These SEs are military officers who are assigned to monitor the long term status of one particular SV subsystem and resolve anomalies as required. They are also the authors of the anomaly case reports which serve as a source of knowledge for NAVARES.

Background on GPS

Mission. The NAVSTAR/GPS is a space-based radio navigation system designed to provide U.S. and Allied land, sea and air forces with worldwide, three dimensional position and velocity information. It also has a Nuclear Detonation (NUDET) detection capability.

Current Operations. Satellite support includes the daily uploading of navigation information into the operative SVs, the monitoring, diagnosis and reconfiguration of all SVs in the GPS constellation, activation of spare SVs, SV station keeping, SV repositioning, and recovery of unstable SVs.

Each SV is provided three navigation uploads per day. Normally, a contact with the SV also includes a State of Health (SOH) support which entails monitoring of the telemetry that indicates the satellite's health. The SOH support must be accomplished four times daily.

A typical contact would consist of a navigation message upload and SOH. The Satellite Analysis Officer (SAO) would prepare the navigation message for sending prior to the pass, while the Satellite Operations Officer (SOO) would prepare to transmit. If any commands were to be sent, the SEO would have generated them and the SOO would also prepare the Ground Antenna (GA) to send these S-band signals. When the satellite is initially contacted by the GA it begins transmitting its telemetry data in real-time, refreshing the information in the telemetry every second. The SOO monitors critical points and calls upon the SEO if there are any indications of a possible problem aboard the SV. The SEO monitors all the telemetry points for possible problems regardless of queries from the SOO. The SEO also records many items for short term trend analysis of the SV's health. If there actually is a problem on the SV, the anomaly resolution process begins. This process will be discussed in detail in the next section.

Once all the commands and/or navigation data is sent and monitoring is completed, the GA ceases its transmission of the S-band signal to the SV and the telemetry downlink automatically terminates after 16 seconds.

Current Anomaly Resolution Process

This section describes the anomaly resolution process. The various types of anomalies are presented and responsibilities of operations personnel defined. The Research and Development (RD) community uses different definitions and terminology than the operational community in describing anomaly categories and procedures, but only the operational community's terms will be used here. The matrix in Table II provides a classification of anomaly resolution responsibilities that may be useful to illustrate this section.

	USERS	SAO	SEO	SOO	SE (ENS)	CREW CMDR
ISSUE REQUIREMENTS	X					
MONITOR AND MAINTAIN NAV PAYLOAD		X				
MONITOR SV HEALTH IN REAL-TIME			X			
PERFORM EMERGENCY ANOMALY RESOLUTION (CAT 1)			X			
PERFORM SHORT TERM TREND ANALYSIS			X			
COMMAND SATELLITE				X		
PERFORM LONG TERM TREND ANALYSIS					X	
ON CALL FOR EMERGENCY ANOMALY RESOLUTION (CAT 1)					X	
PRIMARILY RESPONSIBLE FOR CAT 2 ANOMALY RESOLUTION					X	
PRIMARILY RESPONSIBLE FOR CAT 3 ANOMALY RESOLUTION					X	
APPROVES ALL COMMANDING						X

Table II. NAVSTAR Anomaly Resolution

Types of Anomalies. The 2 SCS Operational Directive on SOH and anomaly resolution lists three categories of anomalies (25).

1. Category 1 - SV life threatening
2. Category 2 - SV mission threatening
3. Category 3 - All others

Table III illustrates these concepts. Contingency actions to correct anomalies are identified as type "A", if the appropriate response to the anomaly is defined in an Operational Directive or the Orbital Operations Handbook (OOH), or type "B", if the response is not documented.

For example, if there was an anomaly detected in the TTC or EPS such that the satellite would permanently lose its operational capability if it were not corrected immediately, then this would be a Category 1 anomaly. If this Category 1 anomaly was one already anticipated by the satellite designers, or one already seen and resolved in the past, then it is likely that there would be a documented procedure in the OOH or Operational Directives for use in resolving this problem. This would be a type "A" contingency action. On the other hand, if an anomaly was encountered in the NAV subsystem that was serious enough to threaten the usefulness of navigation data, but not the health of the SV, it would be called a Category 2 anomaly. If this anomaly was not anticipated by the satellite designers or seen previously, it would likely be a type "B" contingency action.

Table III. Types of Anomalies

	ANOMALY DESCRIPTION	ANOMALY DESIGNATIONS: GPS SOC GPS DIRECTIVE	ANOMALY DESIGNATIONS: AFSCN SOC AND RDBA CONCEPT	CONTINGENCY ACTIONS: GPS SOC GPS DIRECTIVE	CONTINGENCY ACTIONS: OCS/AFSCF INTERFACE PLAN	CRITICALITY: OCS/AFSCF INTERFACE PLAN
		CATEGORY	CLASS	TYPE	PROCEDURE	PRIORITY
GPS SOC GPS DIRECTIVE	SV LIFE THREATENING	1	III	A B	D1 D2 D3	EMERGENCY CRITICAL PRIORITY SIGNIFICANT
	SV MISSION THREATENING	2	III	A B	D1 D2 D3	EMERGENCY CRITICAL PRIORITY SIGNIFICANT
	NON-THREATENING	3	I II	A B	D1 D2 D3	SIGNIFICANT ROUTINE
AFSCF SOC/RDBA CONCEPT	MINIMAL MISSION IMPACT, PROCEDURES AVAILABLE	3	I	A B	D1	SIGNIFICANT ROUTINE
	MINIMAL MISSION IMPACT, NO PREPLANNED PROCEDURES	3	II	A B	D2	SIGNIFICANT ROUTINE
	SV/MISSION THREATENING DIFFICULT TO RESOLVE, SPO EXPERTISE REQUIRED	1 2	III	A B	D3	EMERGENCY CRITICAL PRIORITY SIGNIFICANT

OCS/AFSCF INTERFACE PLAN	
EMERGENCY	Immediate response to prevent permanent loss of the satellite
CRITICAL	Immediate response to prevent unacceptable mission impact or temporary loss of mission capability
PRIORITY	Two hour response to prevent damage to SV health or major impact to the mission
SIGNIFICANT	Support cannot be rescheduled without extensive duplication of effort
ROUTINE	Support that can be rescheduled without serious mission impact

	DESCRIPTION	GPS SOC GPS DIRECTIVE: TYPE	OCS/AFSCF INTERFACE PLAN: PROCEDURE
OCS/AFSCF INTERFACE PLAN	UNDOCUMENTED RESPONSE	A	D2
	DOCUMENTED RESPONSE	B	D1
	EMERGENCY HANDOVER	—	D3

NOTES/REFERENCES

1. Classes of Anomalies: AFSCN SOC and RDBA Concept Implementation Plan
2. Anomaly Resolution Procedures and Priority Definitions: OCS/AFSCF Interface Plan
3. Anomaly Categories: 2 SCS/ENS

SEO Functions. The SEO was described earlier as the crew member performing the first level of anomaly resolution. This is true since in most cases he will be the first person to discover the problem. The SEO checks his displays for telemetry points which are flagged with yellow or red color to indicate a reading out of normal limits.

The SEO's first step would be to draw upon her knowledge of the SV's configuration and health to determine if an anomaly actually existed. Failing to resolve the problem at that point, the SEO may check the OOH for a procedure to follow. If a procedure existed, it would be a type "A" anomaly. Depending on the seriousness of the anomaly, the SEO may recommend immediate action, request support from the on-call SE, or simply make note of the condition so that the appropriate subsystem SE can investigate the matter. If the anomaly were serious enough, and no procedure was available, the SEO may then construct a plan for resolving the problem. To do this, he would again refer to the procedural information in the OOH or Operational Directives. Of course, he may also rely on his general knowledge and training, but the SEO's knowledge is typically more general and shallow than the subsystem expert's, the SE. For this reason, the SEO's are directed to call in the SE's.

SE Functions. The SE's do not work on the operational crews except to maintain proficiency as an operator. They typically spend the majority of their time performing long term analysis of the performance of their particular subsystem on board each SV, increasing their knowledge and understanding of their assigned subsystem, supporting the operational crews by developing contingency plans for possible anomalies, and last, but certainly not least important, resolving anomalies.

The SE's use a variety of software on microcomputers to perform a great deal of their trend analysis and trouble-shooting. Often, they can anticipate problems using this trend analysis, or go back to the trend analysis to investigate an anomaly. They may also rely on the OOH to assist them in resolving a problem, but are more likely to use their knowledge of the history of the satellites and basic engineering skills. For this reason they must be considered the best source of knowledge for NAVARES.

A particularly good source of the SEs' knowledge can be found in the anomaly case reports. Whenever there is a significant anomaly on an SV, one SE, usually the one assigned to the effected subsystem, is assigned to lead the resolution effort. This SE will produce a report of the anomaly upon completion. These reports usually contain a narrative description of the events and describe the logic used to arrive at the conclusion.

Summary

This section has presented some background on GPS and an explanation of anomaly resolution procedures. With the knowledge engineering complete, system requirements can be addressed.

V. System Requirements

Introduction

The system requirements for the prototype, NAVARES, are separated into four categories: input, knowledge base, processing, and output. Tables IV, V, VI, and VII illustrate the results of the system requirements analysis. Each table lists requirements along the left hand side. The columns reflect the current methods of satisfying the requirements, the methods and degree of satisfaction with the thesis prototype, and the methods and degree to which an operational system should satisfy the requirements.

Input

Table IV illustrates the system input requirements. The SEOs record the values of telemetry points during all SOH supports. From these records, as well as the trend plots, the SEs obtain the bulk of the input needed to perform trend analysis and anomaly resolution. It is also possible to play back recordings of telemetry data from recent SOH supports.

An operational system should receive the telemetry data via a computer interface for trend analysis and, perhaps, for raw input to be reasoned over. In general, the prototype will not require telemetry point values as input. It may only require selected points to be entered, needing more conceptual or abstract information about the SV status and environment to reach a conclusion.

Table IV. System Requirements: Input

RQMTS	CURRENT METHOD	THESIS PROTOTYPE	OPERATIONAL SYSTEM
TELEMETRY DATA POINTS & SV STATUS	COMPUTER INTERFACE AND MANUAL ENTRY	- LIMITED SET OF POINTS - INPUT INTERACTIVELY	COMPUTER INTERFACE
MODIFY KB TO REFLECT NEW HEURISTICS	OPERATIONAL DIRECTIVES, OOH UPDATES, AND ANOMALY REPORTS (SEs MANUALLY UPDATE PC FILE WHEN NEW ANOMALY REPORTS ARE GENERATED)	KNOWLEDGE ENGINEER MODIFIES KNOWLEDGE BASE	USER MODIFIES KNOWLEDGE BASE
MODIFY CONFIG. DATA ON SVs	DOV MANUALLY UPDATES "WORDSTAR" FILE	INPUT INTERACTIVELY BY USER	COMPUTER INTERFACE AND INTERACTIVE ENTRY BY USER/DB MANAGERS

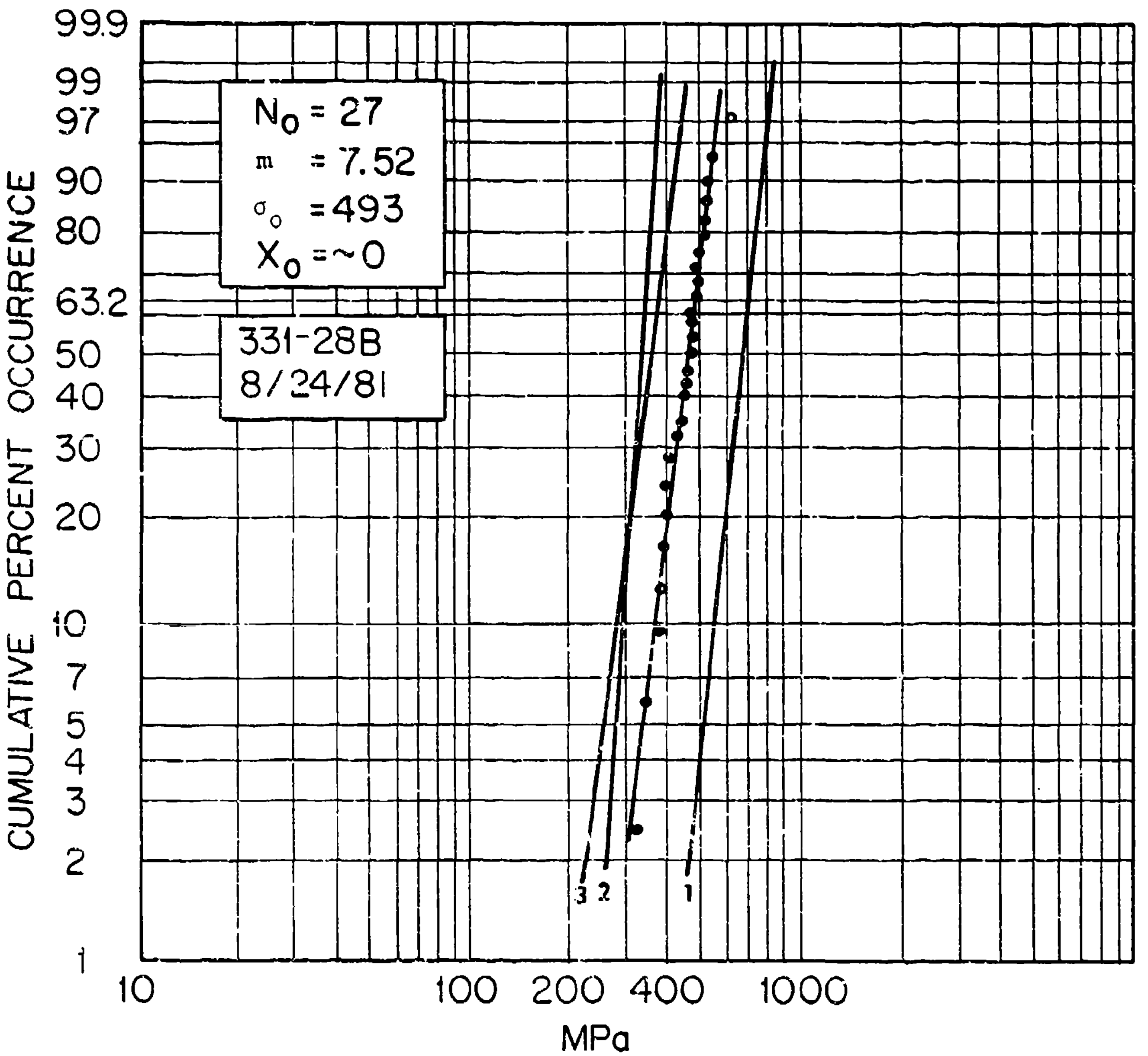


Figure 11. Weibull plot for 331-28B samples from various furnace trays in a single batch. Lines 1,2,3 are for NC203, NC433, and α-SiC as reported in Ref. 9.

With experience, new heuristics for anomaly resolution are formulated. Currently, these new heuristics may be reflected in the Operational Directives, OOH updates, anomaly reports, and the minds of the SEs. For an expert system to be useful, it must be updated to reflect these changes.

As an SV ages, its configuration will change to adapt to failed components or to new mission requirements. The current status of each SV's configuration is maintained by the Standardization and Evaluation section (DOV) in a word processor (Wordstar) file. This knowledge of the SVs' configuration, along with knowledge of each SV's peculiarities, should be incorporated into any system, and must be modifiable to keep it current.

Knowledge Base

Table V illustrates the system knowledge base requirements. As already discussed, past anomaly case reports can provide valuable background for the SE. The thesis prototype includes a data base file of past report titles with associated retrieval keys.

There are three levels of knowledge involved in the anomaly resolution process. There is procedural knowledge that comes from the OOH and Operations Directives which is very much like the knowledge incorporated into a checklist. The second level corresponds to anomaly resolution heuristics which are developed through experience. Such knowledge may also be found in the OOH and Operations Directives, but is more likely to be found in the anomaly case reports and the SEs' heads. The third level of knowledge is much more basic and may be described as reasoning

Table V. System Requirements: Knowledge Base

RQMTS	CURRENT METHOD	THESIS PROTOTYPE	OPERATIONAL SYSTEM
RECORDS OF PAST ANOMALY REPORTS	HARDCOPIES IN CABINETS DATA BASE RECORDS OF RECENT REPORTS	DATA BASE FILE OF PAST REPORTS TITLES	SAME
PROCEDURAL ANOMALY RESOLUTION KNOWLEDGE	OOH AND OPERATIONAL DIRECTIVES	TWO SUBSYSTEMS CAPTURED IN MULTIPLE KNOWLEDGE BASES	NINE SUBSYSTEMS SAME
ANOMALY RESOLUTION HEURISTICS	SE'S EXPERIENCE/KNOWLEDGE, OOH, OPS DIRECTIVES, AND ANOMALY CASE REPORTS	TWO SUBSYSTEMS CAPTURED IN MULTIPLE KNOWLEDGE BASES	NINE SUBSYSTEMS SAME
ENGINEERING/ DESIGN KNOWLEDGE ("FIRST PRINCIPLES")	SE'S EXPERIENCE/KNOWLEDGE	NOT REQUIRED AT PROTOTYPE'S LEVEL OF ABSTRACTION	MODEL-BASED APPROACH

from "first principles." This knowledge is based less on procedures or operational experience and more on an understanding of physical relationships and scientific or engineering laws. This knowledge is found in the SEs' and the satellite designers' minds. It is gained through education and training.

Only the first two levels of knowledge are incorporated into the prototype. An operational system might incorporate the third level of knowledge via the model-based approach. Additionally, an operational system should handle problems with any of the nine subsystems, but a prototype can demonstrate the applicability of expert systems without covering the entire SV. Based on the relative importance and likelihood of failure of each subsystem, the AVCS and EPS were selected for implementation in NAVARES.

Processing

Table VI illustrates the system processing requirements. The individual SE responsible for a particular subsystem of the SV will monitor trending data and produce plots as necessary. As discussed earlier, these plots contribute significantly to the anomaly resolution process, and are created with PC based software. The thesis prototype does not interface with this trend analysis software, but an operational system should include this capability.

The SEs use a PC file to store the more recent anomaly reports. This file allows the user to perform a search for relevant reports. The thesis prototype performs a data base search for the same purpose.

Table VI. System Requirements: Processing

RQMTS	CURRENT METHOD	THESIS PROTOTYPE	OPERATIONAL SYSTEM
PREPARE TREND PLOTS	PLOTS CREATED BY RESPONSIBLE SEs USING PC BASED TOOLS	PLOTS CREATED USING LOTUS 123	GENERATE TREND PLOTS FROM INPUT TELEMETRY DATA POINTS
SEARCH FOR RELEVANT PAST REPORTS	PC FILE SEARCH	DB SEARCH	SAME
DIAGNOSE ANOMALIES FOR EACH SV SUBSYSTEM	SEOs SUPPORTED BY AN SE FOR ALL (NINE) SUBSYSTEMS	TWO SUBSYSTEMS	NINE SUBSYSTEMS
	SE'S BEST GUESS BASED ON ANALYSIS - RUN DIAGNOSTIC TESTS AS REQUIRED	SINGLE SOLUTION	MULTIPLE SOLUTIONS WITH VARYING DEGREES OF CONFIDENCE

The process of diagnosis and remedy of satellite problems is a complex one and varies depending on severity and whether or not a problem was anticipated or seen before. However, one can simplify matters by narrowing the problem to a particular subsystem. Usually, the SE makes his best guess then runs diagnostic tests or conducts analysis to verify his hypothesis. The thesis prototype is more limited in its diagnostic prowess. It only provides one solution to the user. An operational system should suggest any possible solutions to the user indicating which are more probable.

Output

Table VII illustrates the system output requirements. Historical plots of selected telemetry points are very useful to the SE in anticipating and resolving SV anomalies. Currently, there is a computer interface between the mainframe and an IBM PC microcomputer on the MCS operations floor which allows important telemetry points to be loaded onto a floppy disk. The data is then transferred to a Zenith 248 microcomputer in the analysis room adjacent to the MCS operations floor. Here, the SEs can use graphics and spreadsheet software to generate their plots. If the desired telemetry points are not transferred along the computer interface, then the data must be hand plotted or manually entered into the Z-248 for plotting. The thesis prototype does not include the capability to generate these plots, but an operational system should.

Table VII. System Requirements: Output

RQMTS	CURRENT METHOD	THESIS PROTOTYPE	OPERATIONAL SYSTEM
TREND PLOTS	PC BASED SOFTWARE WITH HARDCOPY AND MANUAL PLOTS	PLOTS DISPLAYED OR PRINTED FROM LOTUS 123	SAME
LIST OF RELEVANT PAST REPORTS	HARDCOPY FROM PC BASED FILE SEARCH	HARDCOPY OR DISPLAY FROM DB SEARCH	SAME
CONTINGENCY PLAN	IN OOH OR OPERATIONS DIRECTIVES (TYPE A) OR MANUALLY DEVELOPED BY SE/SEO (TYPE B)	DISPLAY OR PRINT REFERENCING OOH, ANOMALY REPORTS OR RECOMMENDATIONS	SAME + HARDCOPY OF CONTINGENCY COMMAND PLAN
COMPLETED ANOMALY REPORT	MANUALLY CREATED BY SE - LOOSELY FORMATTED - MAY INCLUDE REFERENCES	HARDCOPY AND DISPLAY OF FINAL REPORT AND PAST REPORT SEARCH	BUILT-IN WORD PROCESSOR/ EDITOR AND CAPABILITY TO INCORPORATE TREND PLOTS FOR DISPLAY OR HARDCOPY
SAVE COMPLETED ANOMALY REPORT	HARDCOPIES IN CABINETS (ALL REPTS SINCE 1978) & ELECTRONIC FILE ON PC (ALL REPTS SINCE MAY 1988)	SAVE TO TEXT FILE	SAME + STORE REPORT IN RETRIEVABLE DATA BASE

If they do not already exist in the OOH or Operational Directives, contingency plans for anomaly resolution are developed manually. These plans outline the logic and steps to be taken to diagnose and remedy the problem. They may also include the specific command blocks to be sent to the SV.

The anomaly report is completed by the responsible SE and summarizes the events, logic, and results of a particular anomaly's resolution. The reports have a general format, not a rigid structure. They may include references such as trend plots to illustrate a point or provide background. The thesis prototype provides a final report including the diagnosis, remedy, and results of the past report data base search.

The hundreds of anomaly reports completed while Satellite Control Authority (SCA) resided with the AFSCF are on file in the analysis room in hardcopy form. They are organized chronologically, but are not catalogued. The first 2 SCS anomaly report was created in May 1986, shortly after SCA was transferred to the MCS. Since the SCA transfer the 2 SCS has issued about one dozen reports which they store in hardcopy and electronic form. The thesis prototype saves its final report in a text file. An operational system should allow the user to add text and graphics (trend analysis plots) to the system output.

Summary

The requirements presented in this chapter went through several iterations. They provide the foundation for the system design and will undergo further iterations as a result of the users' evaluation of the thesis prototype.

VI. System Design and Implementation

Introduction

The process of design and implementation translated the requirements presented in the last chapter into a functioning prototype. This chapter provides an overview of this process. The first step was to select the best software tool for development. The second step was to design and implement a prototype to meet the system requirements.

Tool Trade-off Study

The tools selected for examination were limited to those that can be run on an IBM PC compatible microcomputer since the SEs use Z-248s and these machines are also available at AFIT. The tools were also limited to those available at AFIT and those suited to the problem domain of diagnosis and prescription, generally, a tool capable of backward chaining or goal directed inferencing.

Based on the definition of system requirements, the tool required the following attributes.

1. Interfaces with data bases and spreadsheets are required. The capability to interface with external programs and text files is not required, but may prove useful.

2. The tool should be very user friendly. Specifically, it must have an explanation facility, use easily understood syntax rather than cryptic computer code, and be modifiable by the user who is assumed to be experienced in using computers, but not a programmer.

3. Traces and useful error messages can speed development and improve the possibility that the system can be modified by the user.

4. The tool must be relatively inexpensive.

5. The knowledge base requirements include some capability for uncertainty reasoning and the capability to represent knowledge about all nine subsystems for an operational system.

Table VIII lists five tools across the top of a matrix with five feature groupings listed along the left hand side. Turbo PROLOG was included in this table since one of the 2 SCS engineers who may participate in developing NAVARES into an operational system has experience with this programming language. However, as illustrated, it does not have several of the required features.

KES and Insight 2+ would be fair choices, but they do not include the capability to interface with spreadsheet programs or text files. In addition, KES's syntax, while being easier to understand than traditional programming languages, is more cryptic than the remaining tools.

The two tools which satisfied the most requirements were VP Expert and Guru. One major difference between these tools is price. This difference can be explained in part by the fact that Guru includes data bases, spreadsheets, text processing, graphics, a procedural language, statistical analysis software, and many other features. VP Expert only includes the capability to interface with such software as data bases, spreadsheets, and procedural languages. VP Expert is also much more limited in its inferencing strategy, uncertainty reasoning, and user interface.

FEATURES	KES	INSIGHT 2+	VP EXPERT	GURU	TURBO PROLOG
INTERFACE WITH:					
DATA BASES	YES	YES	YES	YES	YES
SPREADSHEETS	NO	NO	YES	YES	NO
EXTERNAL PROGRAMS	YES	YES	YES	YES	YES
TEXT FILES	NO	NO	YES	YES	NO
EXPLANATION	YES	YES	YES	YES	MUST BE PROGRAMMED
CLEAR SYNTAX	FAIR	YES	YES	YES	NO
USER MODIFIABLE	YES	YES	YES	YES	NO
TRACE	YES	YES	YES	YES	YES
ERROR MSGS	YES	YES	YES	YES	YES
COST ($)	4000	500	100	6500	100
UNCERTAINTY	YES	YES	YES	YES	NONE
KB SIZE LIMIT	N/A	N/A	30K/ 20 RULES	N/A	N/A

Table VIII. Tool Selection Matrix

But the most serious limitation for VP Expert is in memory. No knowledge base can exceed approximately 30K of memory or a logical chain of more than 20 rules. The only way to avoid this limitation is to separate the knowledge base into appropriately sized modules which can be linked together by chaining from one to another. The producers of VP Expert claim that this memory limitation will be corrected with the next release.

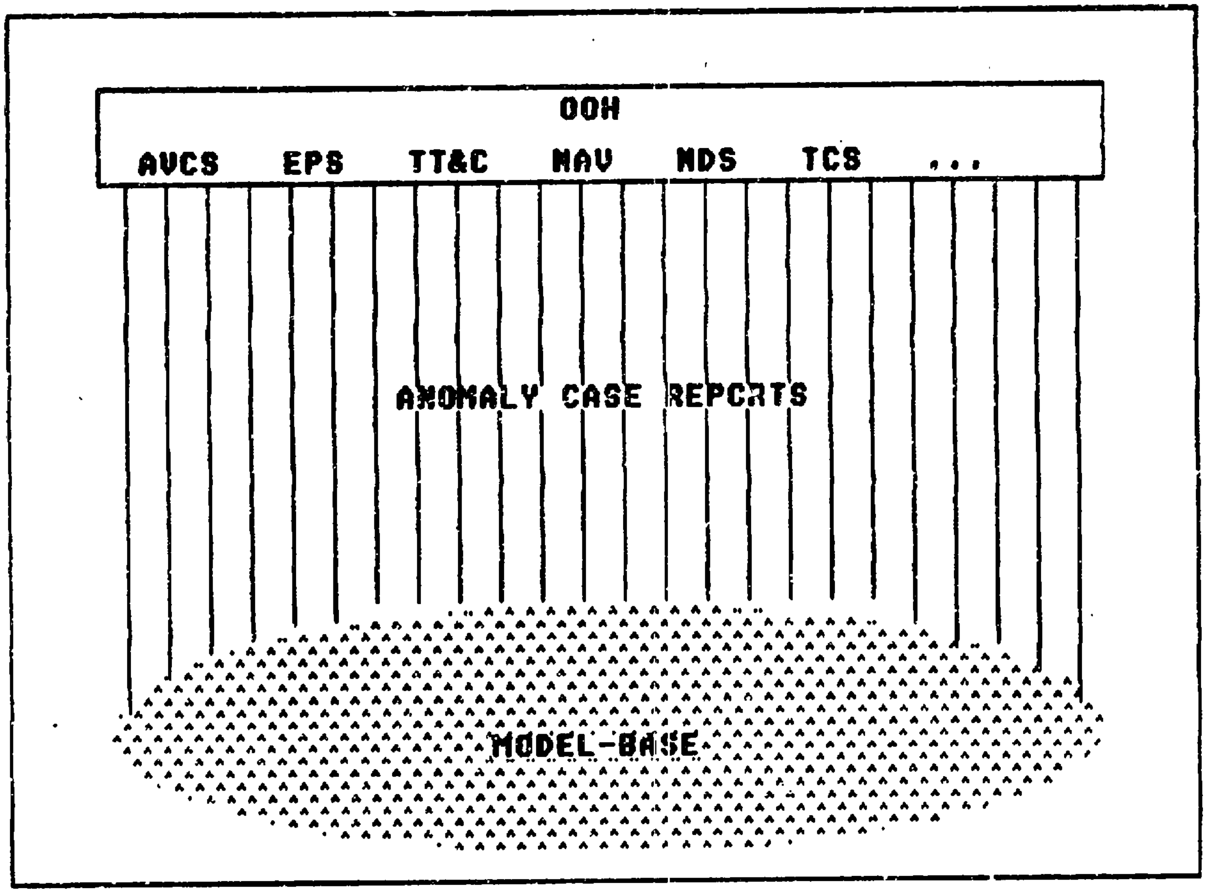
Due to the serious limitations of VP Expert it was not used for this effort. Since Guru is the only tool examined that met all the system requirements it was the tool used to build the prototype.

System Design and Implementation

Introduction. Rapid prototyping was the design strategy used to develop NAVARES. First, several small systems were developed to explore Guru's capabilities. Then a rule set was developed to handle the AVCS. As proficiency with the tool increased, procedural code was added for control, and the remaining rule sets were created. Design was an evolutionary process.

Before the tool trade-off study was conducted NAVARES' system design structure was apparent. Figure 1 illustrates the three levels of knowledge described in the knowledge engineering and system requirements discussion. The current NAVARES prototype is a partial implementation, handling only the AVCS and EPS with no model base. From this high level description it was clear that the operational system would need to incorporate a variety of knowledge representation techniques. However, for the initial prototype the "if-then" rules of Guru would be adequate to

Figure 1. System Design Concept



represent the anomaly resolution heuristics documented in the OOH and past anomaly case reports.

A Guru knowledge base may be composed of rules in one or many files called "rule sets" (20). NAVARES includes seven rule sets which are called by and include Guru procedural code. The majority of the system variables are global so that facts known at any point during the program's execution are available to any rule set. NAVARES also takes advantage of the data management capabilities of Guru by storing titles and retrieval keys for past anomaly reports which may be presented to the user at the end of a session. The remainder of this chapter describes the knowledge representation, data management, user interface, and output. Appendix "A" provides further details which may be needed for system maintenance.

<u>Knowledge Representation</u>. The knowledge engineering process never revealed a standard approach to the process of anomaly resolution. The experts use their experience and knowledge to analyze each anomaly as a unique challenge. Thus, a structure for representing NAVARES' knowledge was induced from a collection of past reports and the OOH. This structure is represented in Figure 2. At the top of the illustration are the subsystems that the user may choose as the suspected culprit in the anomaly. If "Unknown" is chosen, then the system will consider all the possible anomalies included in its knowledge base. If the AVCS or EPS is chosen, then the system restricts its search for a disorder

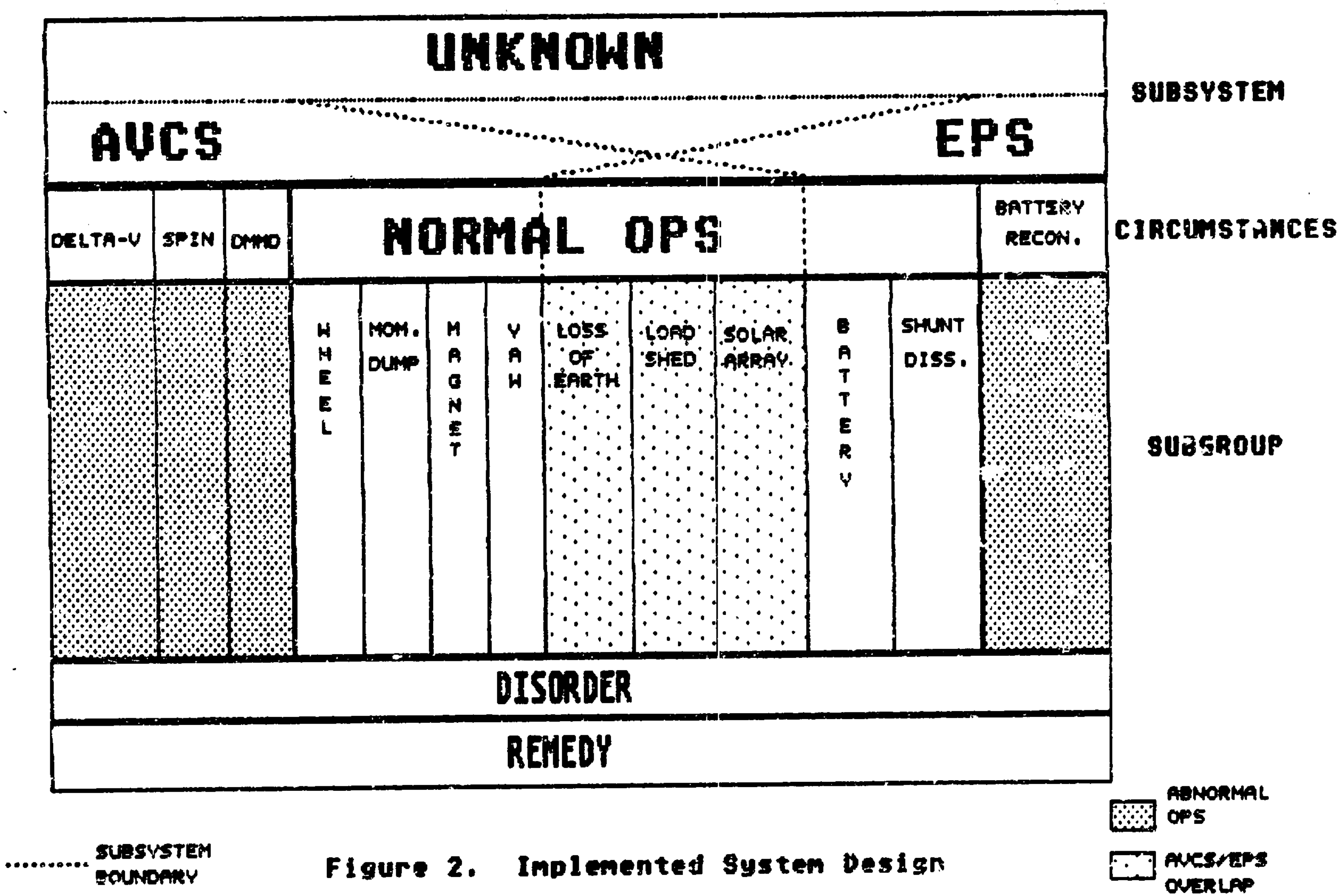


Figure 2. Implemented System Design

and remedy to those anomalies applicable only to the selected subsystem. (NAVARES performs backward-chaining, depth-first search with "remedy" as the goal).

Next, there are five different circumstances from which the user must choose one as the condition under which the anomaly occurred. Note that the largest part of NAVARES' knowledge falls in the "Normal Ops" area. Under the AVCS, the user may also specify Delta-V Maneuver execution, Spin Stabilization, or Dual Magnet Momentum Dump as the circumstance. Under the EPS, he may select Normal Ops or Battery Reconditioning. The four circumstances outside of Normal Ops are logically separate subsets of rules that apply only to these particular circumstances (indicated by the lightly shaded areas). Figure 3 shows a sample rule from this layer of the knowledge base.

```
RULE:     eps1d
          READY:    once
                    @ 3,1 ?"What were the circumstances of the
                            anomalous event?"
                    event = MENU(epsmenu,1,2,7,22,5,36,1)
                    @ 24,1 ?"Thinking... please wait."
          IF:       event = 1
          THEN:     ask1 = true
                    clear
                    @ 3,1 ?"Please narrow the problem to one of
                            the following categories."
                    normvent = MENU(normenu,1,5,5,21,3,38,1)
                    @ 24,1 ?"Thinking... please wait."
                    if normvent ne 5 then epsrun = true
                        perform smallkbs
                    endif
          REASON:   Narrowing search for disorder to particular
                    circumstances.
```

Figure 3. Sample Circumstance Selection Rule

Under Normal Ops, there are nine subgroups. These subgroups correspond to component groups or narrow areas for the system to search for a solution. The three lightly shaded subgroups, (i.e., Loss of Earth, Load Shed and Solar Array), are areas where the EPS and AVCS overlap. This overlap is indicated by the dotted lines. To the left of the lightly shaded subgroups are those subgroups which logically fall under the AVCS. To the right are those which fall under the EPS. This subgroup layer is intentionally portrayed as the thickest since this is the area where the bulk of NAVARES' knowledge resides.

The bottom two layers, "Disorder" and "Remedy," consist of rules which match evidence (i.e., SV status information obtained from the user) to a disorder and a disorder to a remedy, respectively. Figures 4 and 5 show a sample rule from each of these layers.

```
RULE:      mdump4
           IF:        chkhow = true and
                      momhigh = "Y" and
                      mdlon = "Y" and
                      (howflag = "Y" or
                      tbedtemp = "Y")
           THEN:      disorder="uncommanded thruster dump"
                      clear
                      ?"The SV may have experienced an uncommanded"
                      ?"thruster dump.  (See MCS-9794-01)"
                      d1="The SV may have experienced an uncommanded"
                      d2="thruster dump.  (See MCS-9794-01)"
           REASON:    If the momentums on the previous passes were
                      high and building, and the Momentum Dump Logic
                      (MDL) was on, and we had either a flag in the
                      HOW word or high thruster bed temperatures,
                      then we may have had an uncommanded thruster
                      dump.  See MCS-9794-01.
```

Figure 4. Sample Evidence to Disorder Rule

```
RULE:      bat6r
           IF:        disorder="probable battery failure"
           THEN:      remedy = true
                      ?"";?""
                      ?"Turn off the charger to the failed battery."
                      r1="Turn off the charger to the failed
                          battery."
           REASON:    See OOH Figure 3.8.2.3-3.
```

Figure 5. Sample Disorder to Remedy Rule

Figure 2 does not show the organization of the knowledge base into Guru rule sets. NAVARES includes seven rule sets. There are four specific or narrow rule sets which must handle anomalies for Yaw, Battery, Load Shed and Solar Array related problems, respectively. These four may be executed by three more general rule sets for the AVCS, EPS and Unknown subsystem, respectively. This organization allows for manageably sized groups of rules and acceptable execution times.

Execution. Although transparent to the user, NAVARES is driven by goal directed (backward-chaining) inferencing in search of a value for the variable "remedy." To the user it appears that the the first step toward a solution comes in determining which subsystem is the source of the anomaly. Given a selection of the AVCS, the circumstances under which the anomaly occurred must be determined. This narrowing of the solution path by circumstance allows NAVARES to narrow search. If the anomaly occurred under normal operating conditions, then NAVARES must again narrow the source of the problem. For example, after AVCS is selected the problem may be related to a "Loss of Earth" (when the satellite loses its ability to maintain its attitude in space), or one of four other areas. (If the user cannot specify this subgroup as the source of the problem, NAVARES must attempt this selection given the facts available). Under each of the five AVCS normal operations subgroups, may be many possible solution paths for NAVARES to follow. The system may also terminate pursuit of a particular path and search another if the original direction does not lead to any solution.

If the anomaly had occurred under other than normal operating conditions, NAVARES would pursue a solution path under the appropriate circumstance (e.g., Delta-V Maneuver, Spin Stabilization, or Dual Magnet Momentum Dump (DMMD) execution). Again, each circumstance may lead to one of a number of solutions, but in this case NAVARES would not attempt to reach a solution under another set of circumstances if the original selection did not lead to a solution.

NAVARES allows two possible circumstances under which an EPS anomaly may occur: normal operations and battery reconditioning. Given that normal operations is selected, the user of the system may again narrow the set of possible solution paths to one of four subgroups. Of course, as with the AVCS, NAVARES may terminate pursuit of a solution along a given path and pursue another based on the facts available at any time.

Data Management. The data management capabilities of Guru are used to maintain records of past anomaly report titles so that, regardless of NAVARES' success in finding a solution to the problem at hand, the user may request a list of relevant past reports. These reports may be very helpful in providing the satellite engineer clues to the source of an anomaly.

The process of storing and retrieving report titles is relatively simple. Each report is listed as a record in a data base table with fields to identify the circumstances of the anomaly and the subgroup which was involved. At the end of an execution of the prototype, the values of the system's variables (the facts known about the satellites status) will be used to retrieve relevant report titles from the data base. Reports are retrieved on the basis of satellite number, circumstance of anomaly, and subgroup to which the anomaly is related (e.g., Battery, Solar Array, etc.).

User Interface. NAVARES is a very interactive system. The prototype's knowledge about a satellite's current health comes entirely from user input. (See Appendix B for a sample session). The user is first queried for a name, date and SV number (SVN). Next the user is presented with a menu from which he must select the subsystem he suspects to be the source of the problem.

Based on this selection, NAVARES will execute one of the three more general rule sets: AVCS, EPS or Unknown. The next menu will present the user with a choice of circumstances under which the anomaly occurred. These choices will be different depending on which subsystem was chosen. With the circumstances selected, the user must respond to specific questions about satellite subsystem and component status and the current operating environment. If the anomaly occurred while under normal operating conditions, then the user also has the choice of forcing NAVARES to search a narrow solution path or a broad one. He does this by selecting either a subgroup related to the anomaly (e.g., Battery, Solar Array, etc.) or choosing "unknown" and responding to the prototype's queries. The trade-off here is between time of execution and the thoroughness of the search for a solution. It would seldom be wise to narrow the solution path too early and risk pruning a fruitful branch.

Once NAVARES determines that it has found a solution (satisfied the goal), or cannot find a solution (cannot find a value for the variable "remedy"), then it responds by displaying the solution to the user or explaining that the user has exceeded the limits of its knowledge. At any time during the user's interaction with the system he may request an explanation of why NAVARES is requesting information about a particular subject. This explanation is displayed in a window at the bottom of the screen.

The final menu allows the user to display the final report, print the final report, or exit. The final report may, or may not, include a list of relevant past anomaly reports based on the user's indicated preference.

Output. An example of the prototype's output is shown in Figure 6. It gives an assessment of the satellites malfunction (DISORDER) and a suggested solution (REMEDY). In addition, relevant past reports are listed. In the event that NAVARES fails to provide a solution (DISORDER and REMEDY) the user may still request a display or hardcopy of relevant past reports.

```
NAME:                                DATE:                    SVN:
Lt Pam Neal                          14 March 1988            1

DISORDER:
     It is possible that the Solar Array Drive went to hold mode
because of a "bit hit" from cosmic radiation or some other cause.
(See DR SCF 5111-78).

REMEDY:

     If it can be determined that one Solar Array Drive channel is
more susceptible to space charge than the other, then switch to
the less vulnerable channel.  Otherwise, no corrective action can
be suggested.  (See DR SCF 5111-78)


Reports by SVN:
     TITLE

DR SCF 5111-21
DR SCF 5111-35
DR SCF 5111-78


Reports by anomaly type:
     TITLE

DR SCF 5111-78
```

Figure 6. Sample NAVARES Output

VII. Evaluation

Introduction

Perhaps, the greatest value of any initial prototype is in providing a "straw man" for the users so that they might see what they like and do not like. However, before NAVARES was given to the users for an extensive evaluation a more formal verification and validation process was conducted with a representative of the users group. In this context, verification is the process of ensuring that the code works as intended. Validation is the process of determining how accurately NAVARES reflects the real world. Put another way, verification answers the question "Am I building the product right?", while validation answers the question "Am I building the right product?" (5:75) This chapter presents the verification and validation process and a critique of Guru.

Verification

NAVARES' knowledge representation is more complex than a collection of independent solution paths. The branches of the search trees are entwined. Thus, it would be an overwhelming task to test all the possible solution paths exhaustively. Instead, the anomaly case reports and sections of the OOH that served as sources of knowledge were used to verify that the prototype works as intended.

Table IX shows the verification test matrix. The knowledge sources are listed along the left hand side. The symptoms or scenarios presented in each source were input into the system to see if the proper solution was reached. However, NAVARES allows a user to approach a problem from several directions. He may specify AVCS, EPS, or Unknown as the effected subsystem. If the anomaly occurred during normal operations, then the user may also specify a subgroup to search for a solution or he may choose unknown. Moreover, some solutions may be reached through a number of different subgroups. For instance, a space charge anomaly in the Solar Array Drive may cause symptoms that indicate Loss of Earth, Load Shed, and Solar Array related problems. Accordingly, NAVARES allows the user to reach the same solution by choosing any of the latter three possible areas or by choosing "unknown."

For verification purposes, six possible solution paths were specified:

1. AVCS selected, and if circumstances were normal operations, subgroup specified
2. AVCS selected, and if circumstances were normal operations, no subgroup specified
3. EPS selected, and if the circumstances were normal operations, subgroup specified
4. EPS selected, and if the circumstances were normal operations, no subgroup specified
5. Unknown selected, and if the circumstances were normal operations, subgroup specified

6. Unknown selected, and if the circumstances were normal operations, no narrow area or component group specified

CASES	SOLUTION PATHS 1	2	3	4	5	6
DR SCF 5111-21	X	X			X	X
DR SCF 5111-35	X	X			X	X
DR SCF 5111-78	X	X			X	X
DR SCF 5112-21	X	X			X	X
DR SCF 5112-31	X	X			X	X
DR SCF 5112-37	X	X			X	X
DR SCF 5112-38	X	X			X	X
MCS-9721-02	X	X			X	X
MCS-9794-01	X	X			X	X
OOH 3.7.9			X	X	X	X
OOH 3.7.10	X	X			X	X
OOH 3.7.11			X	X	X	X
OOH 3.8.2.3.7			X	X	X	X
OOH 3.8.2.3-1			X	X	X	X
OOH 3.8.2.3-2			X	X	X	X
OOH 3.8.2.3-3			X	X	X	X
OOH 3.8.2.3-4			X	X	X	X
OOH 3.8.2.3-6			X	X	X	X
OOH 3.8.2.3-7			X	X	X	X
OOH 3.8.2.3-8			X	X	X	X
OOH 3.8.2.3-20 (partial)			X	X	X	X

Table IX. Verification Test Matrix

As each case was run, the data base search for past anomaly reports was also checked to ensure that the appropriate report titles were retrieved by SVN and by anomaly.

The verification process revealed no major problems with the prototype's performance. The majority of problems encountered were related to the orderly presentation of information to the user. All the glitches were corrected on the spot. NAVARES works as intended.

Validation

There were four important questions that had to be considered during the validation phase. First, were the knowledge sources valid? Second, were the knowledge sources correctly interpreted and correctly represented in the knowledge base? Third, how much of the necessary knowledge about NAVSTAR AVCS and EPS anomalies had been included in NAVARES' knowledge base? Fourth, how would the prototype perform against unanticipated anomalies, those not already built into the knowledge base? To answer these questions, NAVARES was presented with three scenarios used by the 2 SCS Standardization and Evaluation branch to evaluate the squadron's SEOs and the system was reviewed by a representative from the engineering branch of the 2 SCS performing temporary duty at AFIT.

Validity of Sources. The first question, "Were the knowledge sources valid?", must be answered in the affirmative. However, many of the case reports were written by technicians at the Satellite Control Facility before Satellite Control Authority was passed to the MCS and contain slightly different terminology than that in use at the 2 SCS. The OOH also contains some differences in component names and mnemonics. These differences were limited and do not affect the validity of the system.

Validity of Interpretation. The second question, "Were the knowledge sources correctly interpreted and correctly represented in the knowledge base?", may also be answered in the affirmative, but with exception. This portion of the validation process involved a review by the visiting engineer and presenting NAVARES with the three anomaly scenarios. The 2 SCS engineer did not participate in an exhaustive evaluation of NAVARES' knowledge, nor was this particular engineer the most "expert." However, he has functioned as a qualified SEO and could comment intelligently on the structure and logic of the system.

The engineer felt that the structure and logic of NAVARES was valid with only minor discrepancies. The order in which NAVARES queried the user for information about Loss of Earth, Load Shed, and Solar Array problems did not reflect the priorities and concerns of a satellite engineer presented with the same circumstances. The system was modified so that it will always attempt to solve Loss of Earth problems first, before attending to less critical areas. While the visiting engineer was pleased with the validity of the system this cannot be construed as a final judgement of the systems validity. This judgement must come from the SEs who are personally responsible for the AVCS and EPS.

Beyond this informal evaluation, the engineer supplied three anomaly scenarios used to evaluate SEOs before they may be considered "qualified" for duty. These three scenarios which pertain only to the AVCS AND EPS were:

Scenario 1: Loss of Earth without Load Shed 2 occurrence

Scenario 2: Excessive discharge during Battery Reconditioning/Failure to auto-terminate

Scenario 3: Cosmic radiation caused bit change in Magnet Control Electronics

NAVARES correctly solved scenarios 2 and 3, but could not reach any conclusions for scenario 1. Scenario 2 is covered in a portion of the OOH that was represented in NAVARES' knowledge base, and scenario 3 is covered by a past anomaly report that was also represented in NAVARES' knowledge base. As for scenario 1, NAVARES' knowledge about Loss of Earth was too limited. Loss of Earth may occur as a result of an EPS failure (e.g., Solar Array Drive) that led to Load Shed 2. Load Shed 2 shuts down the AVCS, the subsystem that maintains the SV's attitude. NAVARES could handle such a scenario. But, Loss of Earth may also occur without an EPS failure or Load Shed 2. It may result from an AVCS anomaly. It was this latter scenario that was not accounted for in the knowledge base. This deficiency has been corrected.

Amount of Knowledge. The third question, "How much knowledge is included in the knowledge base?", is answered subjectively. Since there are hundreds of past anomaly reports for NAVSTARs and myriad possible problems that might arise there is no doubt that NAVARES knowledge about AVCS and EPS anomalies is incomplete. The systems performance with the test cases proved this point. But, within the range of possible anomalies, there are those which will occur more often. Figure 7 shows a plot with performance on the vertical axis and knowledge along the horizontal. This curve is not based on scientific analysis, but is meant to illustrate the idea that performance (the percentage of anomalies successfully resolved) increases rapidly if knowledge of common anomalies is incorporated. The slope then decreases as knowledge of less common problems is incorporated. Finally, the curve becomes asymptotic with the perfect performance line reflecting the fact that the range of possible anomalies is seemingly infinite. Some may never be successfully resolved.

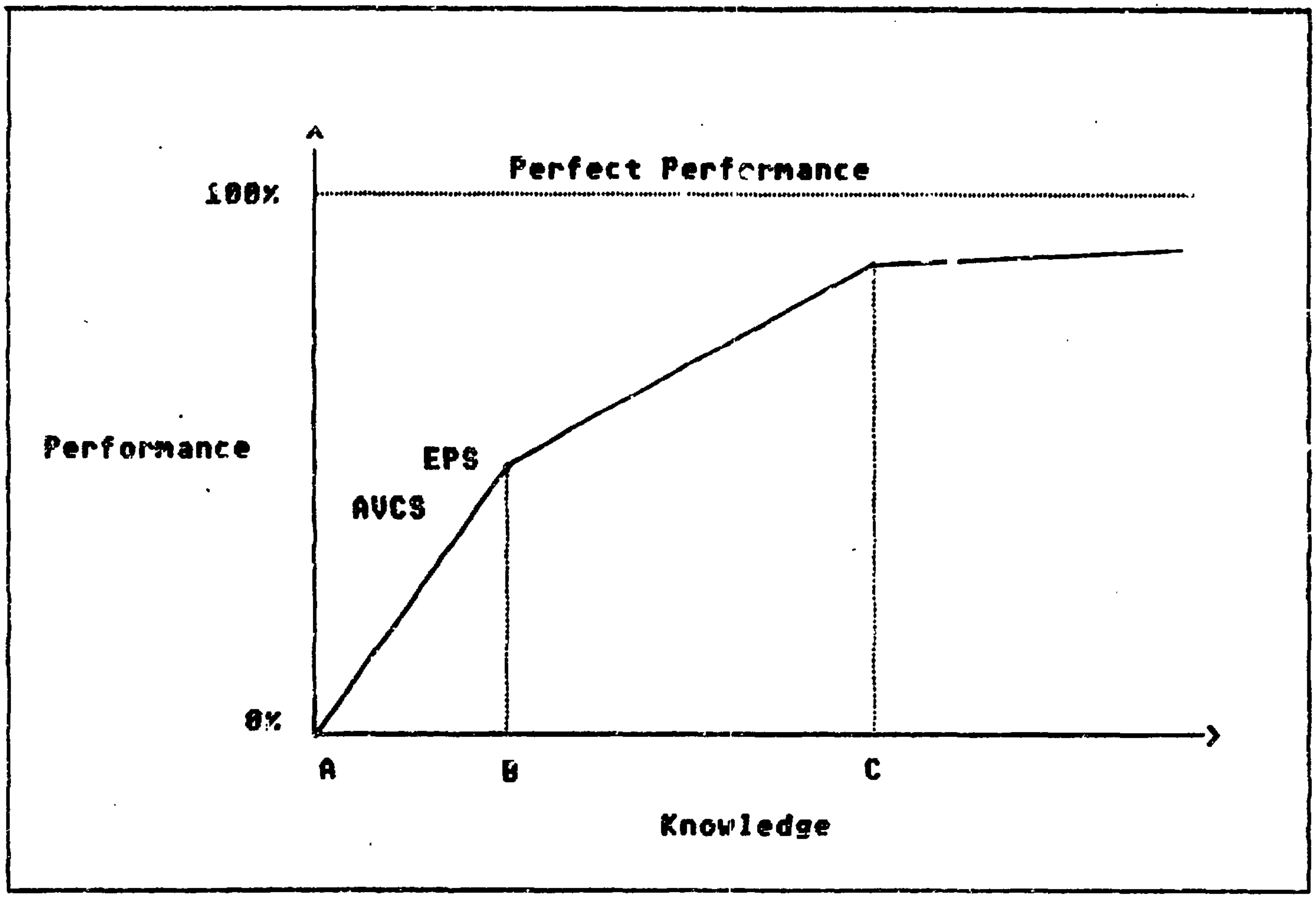


Figure 7. Amount of Knowledge

NAVARES includes nearly 200 unique rules (some are duplicated in different rule sets so the total number of rules is higher), but about two thirds pertain to the EPS. Therefore, the EPS is shown being further along the curve in Figure 7. It may be closer to point "B" than the AVCS. While the amount of knowledge in the system is limited, it provides a very strong foundation for further development. More rules would move NAVARES into the region between "B" and "C", but rules will probably not get the system past "C." This may be achieved using the model-based approach.

Unanticipated Anomalies. The fourth question, "How would the prototype perform against unanticipated anomalies?", is important even though NAVARES is an initial prototype. The way NAVARES handled the first scenario indicates that it performs well - it does not mislead the user. When presented with a set of circumstances that were outside the limits of its knowledge, it simply told the user that he had exceeded the limits of the system's knowledge and provided a list of relevant past reports.

Of course, the potential exists for NAVARES to recognize a few symptoms of an anomaly and make a hasty conclusion. Such a case has not been seen yet, but may arise as development progresses. One way to decrease the potential for damage is to modify the system so that it presents multiple solutions for consideration by the user.

Tool Critique

Guru proved to be a good choice of software for this project. While it does have some disadvantages these are outweighed by its advantages. It must rate as one of the most capable expert system building tools available for PC compatible microcomputers.

Disadvantages. There are three specific disadvantages. First, Guru does not allow variable names longer than eight characters. This seemingly trivial limitation may present the greatest stumbling block to maintainability. Cryptic variable names were created which will serve only to confuse future developers. Second, Guru's advertised spreadsheet capabilities are very limited. In fact, these spreadsheets are so limited in their calculation capabilities that they might more correctly be called data tables.

The third, and most important, disadvantage was Guru's memory management. Early in NAVARES' development, the user was allowed to remain within the Guru environment and repeatedly execute the program. However, with every run of the program less and less RAM was available, and, eventually, the program would not execute properly. Guru includes a "release" command which allegedly clears RAM that may have been used for storing variable values, arrays, etc. Apparently, this command does not function properly. The software producers claim that, if used correctly (taking into account Guru's last-in-first-out memory management), the "release" command should clear the RAM. This developer and two other Guru users spent a great deal of effort attempting to make the "release" work properly with no success. This limitation is the reason why a user is exited from the Guru environment when he exits NAVARES.

Advantages. Guru has many positive attributes. Perhaps, the greatest of these is the control and flexibility afforded the developer by the Guru procedural language. Procedural code may be executed anywhere within a rule set or control the execution of rule sets. This code includes enough constructs to be capable of fairly complex applications and has relatively simple syntax.

Control and flexibility are also increased through the many adjustments available for modifying the inferencing process. Guru gives the developer control of the finest details of inferencing so that the system may be well tailored to a particular application.

With respect to the user interface, control and flexibility are again the key points. Many microcomputer based expert system tools force the developer into a rigid user interface. The visiting engineer who reviewed the system remarked that when interacting with NAVARES it was not obvious that he was running an expert system shell. This is a great compliment and Guru deserves the credit. It was even possible to create subsystem block diagrams and an illustration of a NAVSTAR satellite for display to the user. Guru also includes functions to create menus which add to the friendliness of the system.

For the developer, Guru provides a menu driven interface to perform virtually any task from creating a rule set to editing a data base table. This is a great advantage for the novice, but after a few days one may choose to change development environments to the Guru natural language interface or command prompt.

Overall, Guru was a very good choice. It has a broad range of capabilities and generally performs as advertised. It may take longer to learn how to use than other microcomputer based tools, but the added flexibility and control available are the returns payed on the extra time invested.

VIII. Conclusions and Recommendations

This chapter presents a final review of the research. First, there is a brief synopsis. Then conclusions and recommendations are presented.

Synopsis

The goal of this thesis was to demonstrate the applicability of AI to satellite command and control, specifically, by developing a prototype expert system for NAVSTAR anomaly resolution. It was proposed that, first, an expert system could offer a means of maintaining corporate knowledge in the all "Blue Suit" satellite engineering branch of the 2 SCS. The system could assist the relatively inexperienced satellite engineers in maintaining the operational status of the GPS satellites. Second, the system could take advantage of the "economies of scale" offered by using the NAVSTAR constellation as the target system.

A rule-based prototype was built on a microcomputer using the Guru expert system building tool. The system consists of seven rule sets, three procedural code files, and one data base table. A subjective and objective evaluation process has shown that NAVARES successfully diagnoses many AVCS and EPS anomalies. The system is by no means ready to be used operationally. Much more work needs to be done before that is possible. At this point, the prototype should be used as a point of departure for the users, the satellite engineers, to define their requirements and determine what role AI will play in their decision support systems.

Conclusions

There are four conclusions drawn from this research effort. First, the evaluation process has shown NAVARES to be a successful prototype. If its knowledge is expanded, it can be a useful decision aid in resolving NAVSTAR anomalies. One of the greatest challenges during the development process was determining the structure with which to organize the knowledge about SV anomalies. This structure appears valid and provides a firm foundation to build upon. There will undoubtedly be modifications required based on the users' extensive evaluation.

Second, knowledge engineering was difficult in such a technical and specialized domain. To take NAVARES further toward an operational system will require very close interaction between the satellite engineers (the experts), and the developer. Having a patient and willing expert, and a developer already well versed in the technical details of NAVSTAR operations and the SV's design, will dramatically increase the likelihood of success in developing an operational system.

Third, although Guru is not without its disadvantages, it may very well be the best choice of software for further development. The cryptic nature of its variable names will offer a challenge to system maintenance. The spreadsheet limitations do not pose an insurmountable problem since Guru also interfaces with Lotus 123 which is already available to the users. The system also poses no immediate limitations to growth as Guru allows systems of thousands of rules and the partitioning of knowledge into many interacting rule sets. Perhaps, the only worrisome limitation is the memory management problem encountered. For now, it appears that exiting to the operating system after every run will prevent any difficulties.

Fourth, this research centered on the application of AI to the anomaly resolution process, but it has become clear that another perspective might prove even more useful to the satellite engineers of the 2 SCS. This perspective is to examine their needs in terms of a decision support system (DSS) in which an expert system, such as NAVARES, might play a central role (21). As Figure 8 illustrates, the concept of a DSS consisting of three parts, a model, data, and the man machine interface, would have an expert system as the model, and telemetry and other status information as the data.

Recommendations

The most important recommendation resulting from this research is that the users seriously examine their needs for decision support using the thesis prototype to help define their requirements. NAVARES is not a solution, but demonstrates a technology that has the potential to increase operational effectiveness.

There are four specific recommendations for improvements to the prototype. First, NAVARES' usefulness would be increased by an order of magnitude if it gave multiple solutions with varying degrees of confidence rather than single solutions as it does now. Guru allows for such an extension, and this should be the first step toward an operational system.

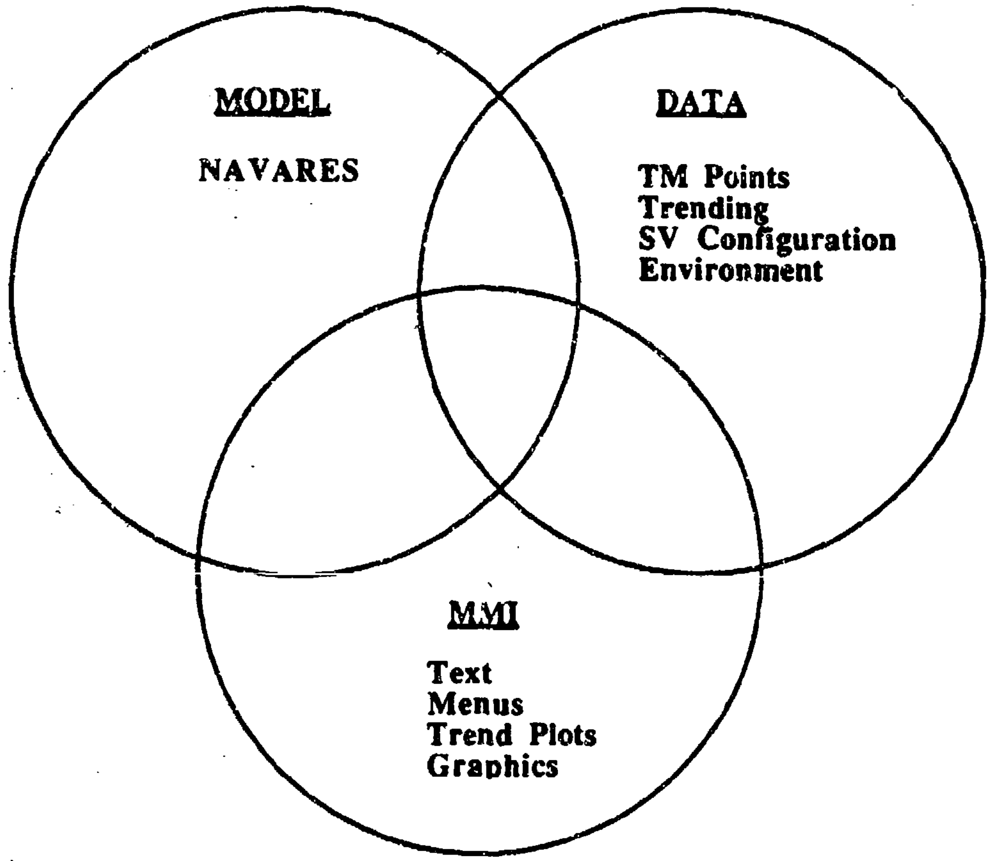


Figure 8. Satellite Engineers' Decision Support System

Second, the system should be expanded to include more knowledge about the AVCS and EPS. And, when the AVCS and EPS are up to speed, the NAV and NDS should be added. These additions would give NAVARES the capability to handle most of the important potential SV anomalies.

Third, Guru has a limited capability for displaying diagrams that may be very useful in improving the user interface. Subsystem or component block diagrams could be displayed with flags to indicate the effected areas or to provide background information to the user.

Fourth, in the long run an anomaly resolution expert system will require access to increasing amounts of data. It will become increasingly cumbersome and time consuming for the user to supply this information at the keyboard. Thus, as the system moves toward operational status it should be interfaced with the data files containing telemetry, status (configuration), and trend analysis information

Summary

NAVARES demonstrates that an expert system can successfully contribute to a portion of the satellite command and control process. It is now up to the users to determine if this approach should be pursued in support of their operations.

Appendix A: Maintenance Guide

The information presented in this appendix should be useful in performing system maintenance. This appendix is not recommended reading for the casual user, but is recommended reading for future developers of NAVARES. A copy of the computer code can be obtained by contacting the Department of Operational Sciences, Air Force Institute of Technology, Wright-Patterson AFB, OH, 45433, (513) 255-3362/2549.

Files and Their Functions

This section describes the files that make up NAVARES and their functions. Within Guru there are several different types of files. NAVARES uses three of these file types.

1. ".ipf" - Perform files - files that contain Guru commands (procedural code), but no rules or tables
2. ".rss" - Rules sets - structured Guru files for executing groups of rules which may also contain procedural code
3. ".itb" - Data tables - data base tables

There are also three ".bat" or batch files accompanying NAVARES. These files contain MSDOS commands.

gps.ipf. This file initializes NAVARES. It declares all the global variables, arrays and forms used during execution. It also presents the first few screens to the user. When the user chooses one of the three subsystems form the first menu gps.ipf executes the appropriate rule set.

avcs.rss. The AVCS rule set contains rules covering many AVCS problems. It is called by gps.ipf if the user chooses "AVCS" as the effected subsystem. If "Yaw related" or "Unknown" is selected, then avcs.rss will call yaw.rss. The rule set "avcs.rss" also calls smallkbs.ipf and search.ipf which will be described later.

eps.rss. The EPS rule set contains rules covering many EPS problems. It is executed by gps.ipf if the user chooses "EPS" as the effected subsystem. If "Unknown" is selected as the subgroup under Normal Ops, then eps.rss will call sa.rss, ls.rss and bat.rss. If "Solar Array," "Load Shed," or "Battery" is selected, eps.rss will call either sa.rss, ls.rss or bat.rss, respectively. This rule set also calls smallkbs.ipf and search.ipf.

unk.rss. The Unknown rule set contains rules covering many AVCS and EPS problems. There is some duplication of rules from the AVCS and EPS, but this duplication is minimized by calling the same yaw.rss, sa.rss, ls.rss and bat.rss rule sets that are called by the AVCS and EPS rule sets. The Unknown rule set also calls smallkbs.ipf and search.ipf. It is executed when the user selects "Unknown" from the first menu which asks the user to identify the effected subsystem.

sa.rss. This rule set contains rules covering Solar Array related problems. It may be called by either the EPS or the Unknown rule set. The perform file "smallkbs.ipf" is actually called by the higher level rule sets and, in turn, executes sa.rss. The Solar Array rule set does not call any other files itself. It will return to execution of the EPS or Unknown rule set depending on which was the "caller."

ls.rss. This rule set contains rules covering Load Shed related problems. It may be called by either the EPS of Unknown rule set. The perform file "smallkbs.ipf" is actually called by the higher level rule sets and, in turn, executes ls.rss. The Load Shed rule set does not call any other files itself. It will return to execution of the EPS or Unknown rule set depending on which was the "caller."

bat.rss. This rule set contains rules covering many Battery related problems. It may be called by either the EPS or Unknown rule set. The perform file "smallkbs.ipf" is actually called by the higher level rule sets and, in turn, executes bat.rss. The Battery rule set does not call any other files itself. It will return execution to the EPS or Unknown rule set depending on which was the "caller."

yaw.rss. This rule set contains rules covering Yaw related problems. It may be called by either the AVCS or Unknown rule set. The perform file "smallkbs.ipf" is actually called by the higher level rule sets and, in turn, executes yaw.rss. The Yaw rule set does not call any other files. It will return execution to the AVCS or Unknown rule sets depending on which was the "caller."

smallkbs.ipf. This procedural code file may be called by avcs.rss, eps.rss or unk.rss. It contains conditional statements that will execute one or more of the four lower level rule sets (i.e., sa.rss, ls.rss, bat.rss, and yaw.rss). Upon completion of this perform file, the calling rule set (avcs.rss, eps.rss, or unk.rss) continues execution at the point following its call to smallkbs.ipf.

search.ipf. This perform file may be executed by either the AVCS, EPS, or Unknown rule sets. The file "search.ipf" is executed in the completion conditions of the rule sets (executed after NAVARES has found a solution or has determined that it cannot find a solution). It contains procedural code for retrieving past anomaly report titles from the past report data table (pr.itb) based on SVN, circumstance of the anomaly (NAVARES variable "event"), and anomaly type (NAVARES variable "normvent") if circumstances were normal operations.

pr.itb. This data table contains nine fields. The first field contains the past report title which is retrieved for the user based on the values of the remaining eight fields.

Field Name	Description
TITLE	Past report title
SUBSYS	Effected subsystem
SATNUM	Satellite vehicle number
UNKCOND	Anomaly Circumstances (unk.rss run)
UNKNORM	Anomaly type or subgroup (unk.rss run)
AVCSCOND	Anomaly Circumstances (avcs.rss run)
AVCSNORM	Anomaly type or subgroup (avcs.rss run)
EPSCOND	Anomaly Circumstances (eps.rss run)
EPSNORM	Anomaly type or subgroup (eps.rss run)

Retrieval of reports by SVN is straightforward, but retrieval by the remaining fields is less obvious. (The field "SUBSYS" is not actually used for report retrieval, but is included as a "hook" that might be used in future development to retrieve reports by effected subsystem.) When the user chooses the circumstances of the anomaly (e.g., Normal Ops, Delta-V, etc.) the variable "event" is set equal to the number of the choice on the menu. This variable ("event") is matched against UNKCOND, AVCSCOND or EPSCOND to retrieve reports depending on which subsystem rule set was executed. Each rule set has a "XXXCOND" field since the menus are different for each one. The UNKNORM, AVCSNORM, and EPSNORM fields are matched against the NAVARES variable "normvent" for report title retrieval. When the user chooses a subgroup under Normal Ops the variable "normvent" is assigned the number of the choice on the menu. Since the menus are different in the three subsystem rule sets there are three "XXXNORM" fields in pr.itb.

<u>prsvn.itb, prevent.itb, prnorm.itb</u>. These three data tables do not exist prior to the execution of NAVARES. They are created by the search.ipf perform file upon its execution. They will hold the past report titles retrieved based on the values of the variables "svn," "event," and "normvent," respectively. If there are no reports found based on a search, then the corresponding table will not be created. For example, if the user lists "7" as the SVN and pr.itb has no reports for SATNUM=7, then the table "prsvn.itb" will not be created. With each execution of NAVARES these three data tables are deleted then re-created.

epsdia.ipf, bccdia.ipf, batdia.ipf. These three perform files actually contain the definitions of component diagrams of the EPS. They are executed in demonstration cases to visually indicate the malfunctioning component to the user.

startup.ipf. This perform file is immediately executed upon entering the Guru environment. With NAVARES, gps.ipf is copied into this file so that the user does not have to learn any Guru commands to execute the program. He simply types "ens" at the MSDOS prompt and NAVARES is executed.

ens.bat This file contains the command that must be typed at the MSDOS prompt to execute Guru ("guru -g"). Again, its function is to keep the user from having to learn Guru commands.

in.bat, out.bat. These "batch" files contain MSDOS commands that will transfer all the files necessary for NAVARES execution (not including the Guru software itself) to and from the user's hard disk (assumes floppy drive labeled "A" and hard disk labeled "C").

Key Variables

This section describes the key variables used in NAVARES.

"event". This numeric variable is used in each of the three subsystem rule sets: avcs.rss, eps.rss, and unk.rss. It is the first variable that assumes a new value in an execution of the program, and its value is a number which corresponds to the users choice of circumstances under which the anomaly occurred (the number from the circumstance menu). For instance, in the EPS rule set event may equal "1" or "2" since the user may only choose "Normal Ops" or Battery Reconditioning." In the Unknown rule set, event may equal a number from one through five. Once the circumstances are known (event=i), then the possible solution paths can be narrowed. For example, if event=2 in the EPS rule set, then only rules pertaining to these conditions (Battery Reconditioning) will be considered. This shortens execution time and prevents inappropriate queries.

askі (i = 1, 2, 3, 4, 5). When a value is obtained for the variable "event" there is a corresponding value set for the variable "aski." If Normal Ops is selected, event is set equal to "1" and "ask1" is set to "true." If event were set equal to "2," then "ask2" is set to "true." This variable simply allows for a logical separation of rules so that the system will never attempt to ask the user for information that is not relevant to the selected circumstances under which the anomaly occurred. For cases where i = 2, 3, 4, or 5, "aski" is the last variable used to logically separate rules. The remaining rules seek evidence of an anomaly. But, for i = 1, the Normal Ops case, more logical separation occurs.

"normvent". Assuming that the user has selected "Normal Ops" as the circumstance under which the anomaly occurred, NAVARES attempts to narrow the possible solution paths even further. The user is asked to choose one of up to ten subgroups (avcs.rss has six subgroups, eps.rss has five) including the option "Unknown." The variable "normvent" is set equal to the number corresponding to the user's selection of subgroup from the menu. If the user selects any subgroup other than Unknown, then NAVARES will pursue solution paths which pertain only to that subgroup and disregard other possibilities. If the user chooses Unknown, then all subgroups are included in the search for a solution. This process of narrowing the search is affected by the next variable.

"chkzzz". Just as aski (i = 1, 2, 3, 4, 5) was used to logically separate rules that pertained to different circumstances, chkzzz is used to logically separate rules that pertain to different subgroups. For instance, in unk.rss, if the subgroup "Load Shed" is selected (normvent=1), then the variable "cnkldshd" is set to "true." On the other hand, if the user selects "Unknown," then all the "chkzzz" variables are set to "true" and NAVARES considers all subgroups in searching for a solution. The subgroups and their corresponding "chkzzz" variables are as follows:

1. Load Shed - chkldshd
2. Solar Array - chksac
3. Battery - chkbat
4. Shunt Diss. - chksdv
5. Loss of Earth - chksafe
6. Magnet - chkrmagl
7. Reaction Wheel - chkwheel
8. Momentum Dump - chkcmd
9. Yaw - chkclips

The remaining NAVARES variables are defined in the gps.ipf perform file. The future developer should also keep in mind the fact that NAVARES is backward-chaining in search of a value for the variable "remedy." While it is simpler to think in terms of narrowing the search from circumstance to subgroup, subgroup to evidence, evidence to disorder, and disorder to remedy, the system is actually searching in the opposite direction.

Past Report Table Updating

As discussed earlier, the search.ipf perform file is executed at the end of the Unknown, AVCS, and EPS rule sets. This program retrieves past report titles from pr.itb based on the values of the variables "svn," "event," and "normvent." The values for event and normvent will vary between the three subsystem rule sets so there are corresponding fields in pr.itb for each rule set (see discussion of pr.itb in "Files and Their Functions"). If "Unknown" was chosen as the subgroup, then procedural code is executed at the end of each subsystem rule set that assigns a new value to normvent based on the information presented to NAVARES during execution. This new value assigned to normvent will correspond to a particular subgroup identified as the source of the anomaly. This value of normvent will then be used by search.ipf to match against the fields "UNKNORM," "AVCSNORM," or "EPSNORM" depending on which rule set had been executed.

To update or expand pr.itb a new record in the table should be created with appropriate values in each field. For instance, a new report for SVN 6 should be entered with the title under the "TITLE" field and a "6" in the "SATNUM" field. If the new report pertained to the AVCS, then "AVCS" should be entered in the "SUBSYS" field. If the report pertained to a Loss of Earth problem that occurred under normal operating conditions, then enter "1" in the "UNKCOND" field (corresponds to "Normal Ops" and event = 1), "5" in the "UNKNORM" field (corresponds to "Loss of Earth" subgroup and normvent = 5), "1" in the AVCSCOND field and "1" in the AVCSNORM field. There is no corresponding subgroup under the EPS, but the developer may also want to list this report for Load Shed problems. In this case, enter "1" in the "EPSCOND" field (corresponds to "Normal Ops" and event = 1), and "1" in the "EPSNORM" field (corresponds to "Load Shed" subgroup and normvent = 1). (The appropriate number to enter in any of the last six fields can be determined by examining the particular rule set's menu).

Of course, the same report may be listed in several records if it is relevant to multiple circumstances or subgroups. In any case, the developer must ensure that the values entered in the table for "XXXCOND" and "XXXNORM" correspond to the values of event and normvent for each subsystem rule set.

Appendix B: User's Guide

This user's guide is presented with the assumption that the Guru software has already been loaded into the user's system and that a Guru directory has been created. It is also assumed that the user has installed Guru on a Z-248 or other IBM PC compatible microcomputer with the floppy disk drive labeled "A" and the hard disk drive labeled "C."

Installation

There are 14 files which must be loaded onto the user's hard disk for NAVARES execution.

1. unk.rss	6. bat.rss	11. epsdia.ipf
2. avcs.rss	7. yaw.rss	12. bccdia.ipf
3. epsdia.rss	8. gps.ipf	13. batdia.ipf
4. sa.rss	9. smallkbs.ipf	14. pr.itb
5. ls.rss	10. search.ipf	

There are also three "batch" files of MSDOS commands that should be useful: ens.bat, in.bat, and out.bat. The maintenance guide in Appendix A provides a description of each file.

To copy all the necessary files onto the user's system simply execute the in.bat batch file by typing "in" at the A drive prompt or by copying the in.bat batch file into the Guru directory and then typing "in" at the "C\GURU" prompt.

Once all the necessary files have been copied into the Guru directory, the gps.ipf file should be copied into filename "startup.ipf." Guru will automatically execute any file named "startup.ipf" when it is initialized. With all the files transferred and startup.ipf created NAVARES is ready for execution.

Execution

To execute NAVARES the user must type "ens" at the C\GURU prompt. This command will initialize the Guru environment and begin a NAVARES session. The first few screens provide an introduction to NAVARES and ask for the user's name, the date, and the SVN. When NAVARES prompts the user for information, whether it be "Y" or "N", or the user's name, the information should be typed at the keyboard and entered by pressing the "Return" key.

The first point where the user must make an important decision is at the menu which asks for the anomalous subsystem (see Figure 9). Here the user must choose to narrow the search for a solution or enter "Unknown." Selections are made from all menus by pressing the number key corresponding to the user's choice or by using the keyboard arrows to highlight the user's choice before pressing the "Return" key.

```
Does this anomaly seem to be in the AVCS or EPS?

     1.  Attitude, Velocity and Control Subsystem
     2.  Electrical Power Subsystem
     3.  Unknown
```

Figure 9. Subsystem Menu

For the purposes of this discussion, assume the AVCS is selected. The next menu will then prompt the user for the circumstances under which the anomaly occurred (see Figure 10). The user does not have the option of answering "Unknown" in this case.

```
What were the circumstances of the anomalous event?

        1.  Normal Operations
        2.  Delta-V maneuver
        3.  Spin stabilization
        4.  DMMD execution
```

Figure 10. Circumstances Menu

Assuming that "Normal Operations" was selected, the user is then asked to narrow the problem to a particular subgroup (see Figure 11). For this example assume "Loss of Earth" is selected. Of course, determining the subgroup may not be possible or prudent so the user may select "Unknown."

```
Please narrow the problem to one of the following
categories.

        1.  Loss of Earth
        2.  Magnet related
        3.  Reaction Wheel related
        4.  Momentum dump related
        5.  Yaw related
        6.  Unknown
```

Figure 11. Subgroup Menu

Once the subgroup is selected, the user will then be presented a series of questions to help NAVARES reach a solution. Figure 12 shows the sequence of questions and the answers (underlined) given by the user in this example. (The user should note the comment "Thinking... please wait" in the lower left of the screen after each answer is entered. Do not make any entries while this message is displayed.)

> Are the pitch and roll error less than or equal to
>
> 2 degrees? (Y/N) <u>N</u>
>
> (new screen)
>
> Is the pitch and roll override enabled? (Y/N) <u>N</u>
>
> (new screen)
>
> The SV has experienced loss of earth.
> No attempt should be made to diagnose the SV until it is
> safed.
>
> Press any key to continue.
>
> (new screen)
>
> Has Load Shed 2 occurred? (Y/N) <u>Y</u>
>
> (new screen)
>
> Is the solar panel gimbal angle appropriate for the position
>
> in the SV's orbit where Load Shed 2 occurred? (Y/N) <u>N</u>

Figure 12. Sample Query Sequence

This particular sequence of questions leads to a solution which is displayed after the last question is answered. The user is then presented with a block diagram of the EPS indicating the anomalous component. The visual indication is only available for three demonstration cases: the case described here, the case of excessive discharge during battery reconditioning, and the case of a probable battery failure. The next screen displayed allows the user to view and print the desired output.

Output

Figure 13 shows the final menu. From this point the user can view the final report and results of the past anomaly report search, print this information, and exit. If "Display Report" is selected, the final report is displayed and at the bottom of the screen a message appears asking the user if he would like to view the results of the past report search. Typing "N" will return the user to the final menu. Typing "Y" will cause NAVARES to present the results of the search before returning the user to the final menu. From here, the user may choose to print the report and search results or simply exit.

```
1.  Display Report
2.  Print Report
3.  Exit
```

Figure 13. Final Menu

Menu Selections

The user should be aware that it is possible to reach the same solution following different paths. For example, the solution described above could have been reached by selecting AVCS from the subsystem menu and "Unknown" from the subgroup menu. In addition, the user could have selected "Unknown" from the subsystem menu and "Loss of Earth" or "Unknown" from the subgroup menu to reach the same solution.

There is a trade-off between narrowing the problem immediately and choosing "Unknown" from the menus. Narrowing the problem will decrease the number of questions asked of the user and speed execution time. However, narrowing the problem may also deprive the user of the correct solution since NAVARES will ignore possible solutions outside of the specified subsystem and subgroup.

Summary

This user's guide provides a brief introduction to NAVARES execution. The maintenance guide contains more detailed information on files and their functions, key variables, and data table updates. The System Design and Implementation chapter also provides further explanation for the interested user.

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VITA

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